Universitat Autònoma de Barcelona

SHERPA ENGINEERING
269-287, rue de la Garenne - 92024 Nanterre Cedex
Tel. +33 1.47.82.08.23 - Fax +33 1.47.82.00.96
SA au capital de 412.400 € - APE : 742 C- SIRET : 413 367 228 00017

TECHNICAL NOTE 95.2

MELISSA Pilot Plant Higher Plants Chamber: elaboration of the control system on simulator

Prepared by/Préparé par	Gerbi, O. and Leclercq, J.J.
Reference/Réference	MELiSSA Pilot Plant Frame Contract 19445/05/NL/CP
Issue/Edition	0
Revision/Révision	0
Date of issue/Date d'édition	26/08/08
Status/Statut	Final

MELiSSA

TECHNICAL NOTE 95.2

APPROVAL

Title *Titre*	**MELISSA Pilot Plant Higher Plants Chamber: elaboration of the control system on simulator**	Issue *Edition*	0	Revision *Révision*	0

(O. GERBI)

Prepared by *Auteur*	Gerbi, O. and Leclercq, J.J.	Date *Date*	26/08/08

Checked by *Verifié par*	Peiro, E. and Fossen, A. Enrique Peiró	Date *Date*	26/08/08

Approved by *Approuvé par*	Gòdia, F.	Date *Date*	26/08/08

Approved by customer *Approuvé par le client*	Lamaze, B.	Date *Date*	26/08/08

CHANGE LOG

Issue/*Edition*	Revision/*Révision*	Status/*Statut*	Date/*Date*
0	0	Final	26/08/08

Distribution List

Name/*Nom*	Company/*Société*	Quantity/*Quantité*
Brigitte LAMAZE	ESA	2 hardcopies + electronic version

TABLE OF CONTENT

SHERPA ENGINEERING
269-287, rue de la Garenne - 92024 Nanterre Cedex
Tel. +33 1.47.82.08.23 - Fax +33 1.47.82.00.96
SA au capital de 412.400 € - APE : 742 C- SIRET : 413 367 228 00017

SECTION 1

MELISSA Pilot Plant Higher Plants Chamber: elaboration of the control system on simulator

Prepared by/Préparé par	Olivier Gerbi, Jean-Joseph Leclercq
Reference/Référence	ESA/UAB Contract 19445/05/NL/CP
Issue/Edition	1
Revision/Révision	0
Date of issue/Date d'édition	August 2008
Status/Statut	Final

APPROVAL

Title *Titre*	**MELISSA Pilot Plant Higher Plants Chamber: technical requirement of the control system**	Issue *Edition*	1	Revision *Révision*	0

Author *Auteur*	Olivier Gerbi & Jean-Joseph Leclercq	Date *Date*	26/08/2008

Approved by *Approuvé par*		Date *Date*	

CHANGE LOG

Reason for change	Issue/*Edition*	Revision/*Révision*	Status/*Statut*	Date/*Date*
Creation	1	0	Draft	May 2007
Update	1	0	Final	August 2008

Distribution List

Name/*Nom*	Company/*Société*	Quantity/*Quantité*
F. Gòdia	UAB	
J. Mas	NTE	
M. Dixon	UoG	
Melissa Partners		

TABLE OF CONTENT

TABLE OF FIGURES

TABLE OF TABLES

1. Introduction

The first High Plant Compartment (HPC) is being constructed at the University of Guelph, one of the members of the MELISSA consortium.
Before its final transfer to the Melissa Pilot Plant (MPP) located at the premises of Universitat Autònoma de Barcelona (UAB), the HPC will be functionally tested with its own Control System, Argus, in Guelph.
According to a harmonization approach, same systems should be used in all the compartments. Black Box HPC control will be replaced with a White Box control system.
The main objective of the control is to pilot the light, CO2 concentration, temperature, humidity, conductivity and pH in the plant compartment.
The first objective of the study was to develop the control laws in simulation, implement them in Schneider PLC Quantum with its electric hardware and do the validation at Guelph site.
During the project, the validation in Guelph was abandoned. The validation and implementation will be done in Barcelona, Spain.
Sherpa (France) with the partnership of NTE (Spain) perform this work, in addition of UAB as Prime Contractor

Specific Objective of this Technical Note is to detail the control strategies for each control loops.

When needed for a best definition of the control design, mainly for Level 1 control loops like: Temperature and Humidity, CO2, pH, EC, a simulator is built for performing tests.

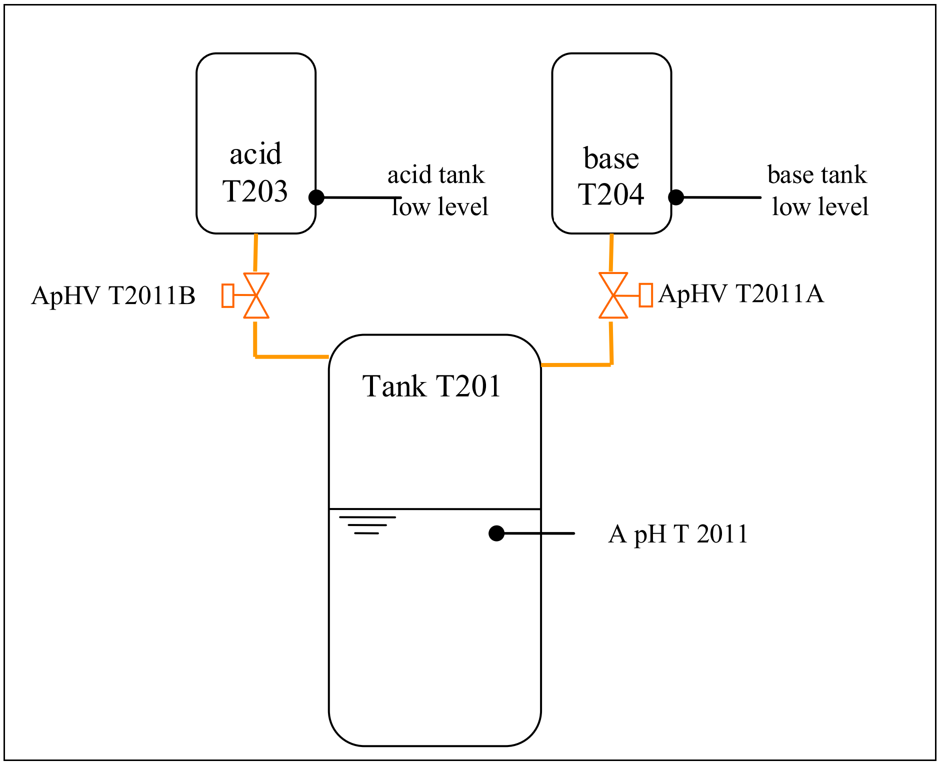
Reference document for the elaboration of this technical note:
TN95.1: MPP Higher Plants Chamber: technical requirement of the control system.

Inputs for this document is mainly based on the

- TN85.5 : Detailed Design and Verification (G. Waters, UoG, A. Masot, UAB),
- Meetings betweens partners
- TN72.2 : Definition of the control requirements for the MELISSA Loop (NTE)
- TN72.4 : Control System Demonstrator Data Package (Jordi Duartis, NTE)
- Minutes of Meeting 02 July 2007 ESA/UoG/Sherpa
- P&ID Draft by Geoffrey Waters July 30 2007
- Technical Documentation : Coils B301 and B302. Main Centrifugal Fan.

2. PH Control

The pH must be kept between two limits



The pH is regulated by means of added strong acid (xN HCl) or strong base (xN NaOH) contained in two bottles.

2.1.1.Control

2.1.1.1. *Specification*

- Constraints:
  - $5 < pH < 6$

2.1.1.2. *Control strategy*

- A split-range strategy based on a PCR (Predictive Controller) regulator is implemented in the PLC.

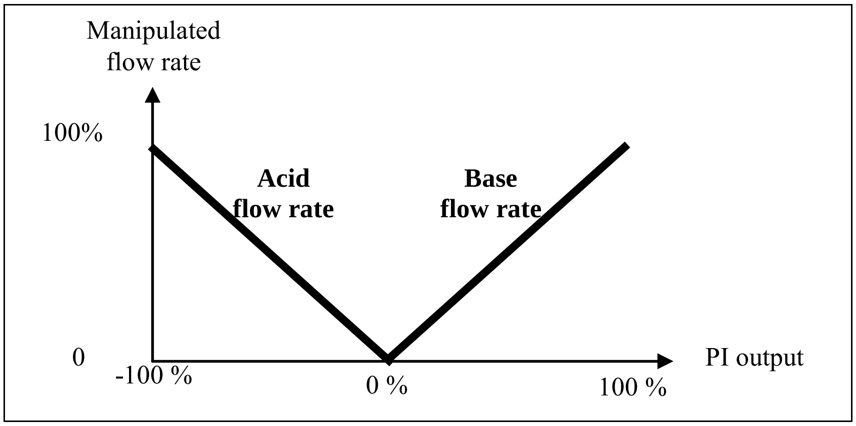


Figure 1: split-range between acid and base

- The control period is 10 min.
- An on-off control is used, by means of PWM (Pulse Width Modulators), whose maximum active times are 5 min. This prevents from continuously adding reagent. The control period is 10 min, and the active time of the PWM is limited to 5 min:

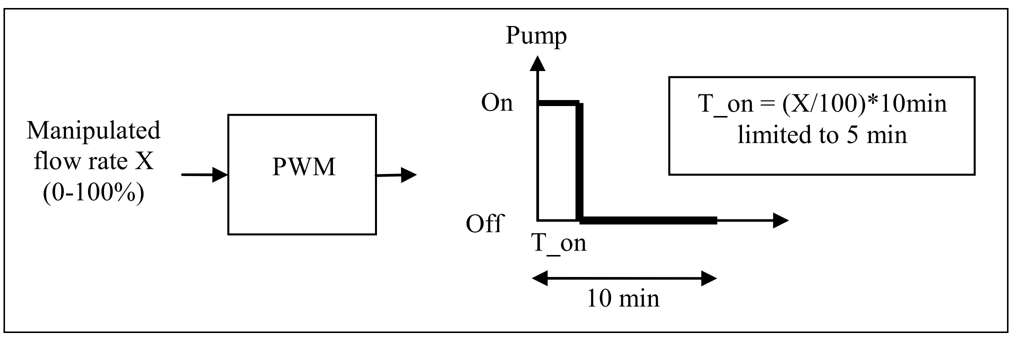


Figure 2: pH on-off control

- A dead-zone strategy is implemented. No reagent is added if the absolute value of the error between the pH and its set-point is less than the dead-zone value (typically 0.03).

2.2. Model

2.2.1.Structure, equations and parameters

The pH model of the bioreactor and its environment and control is developed with Simulink.

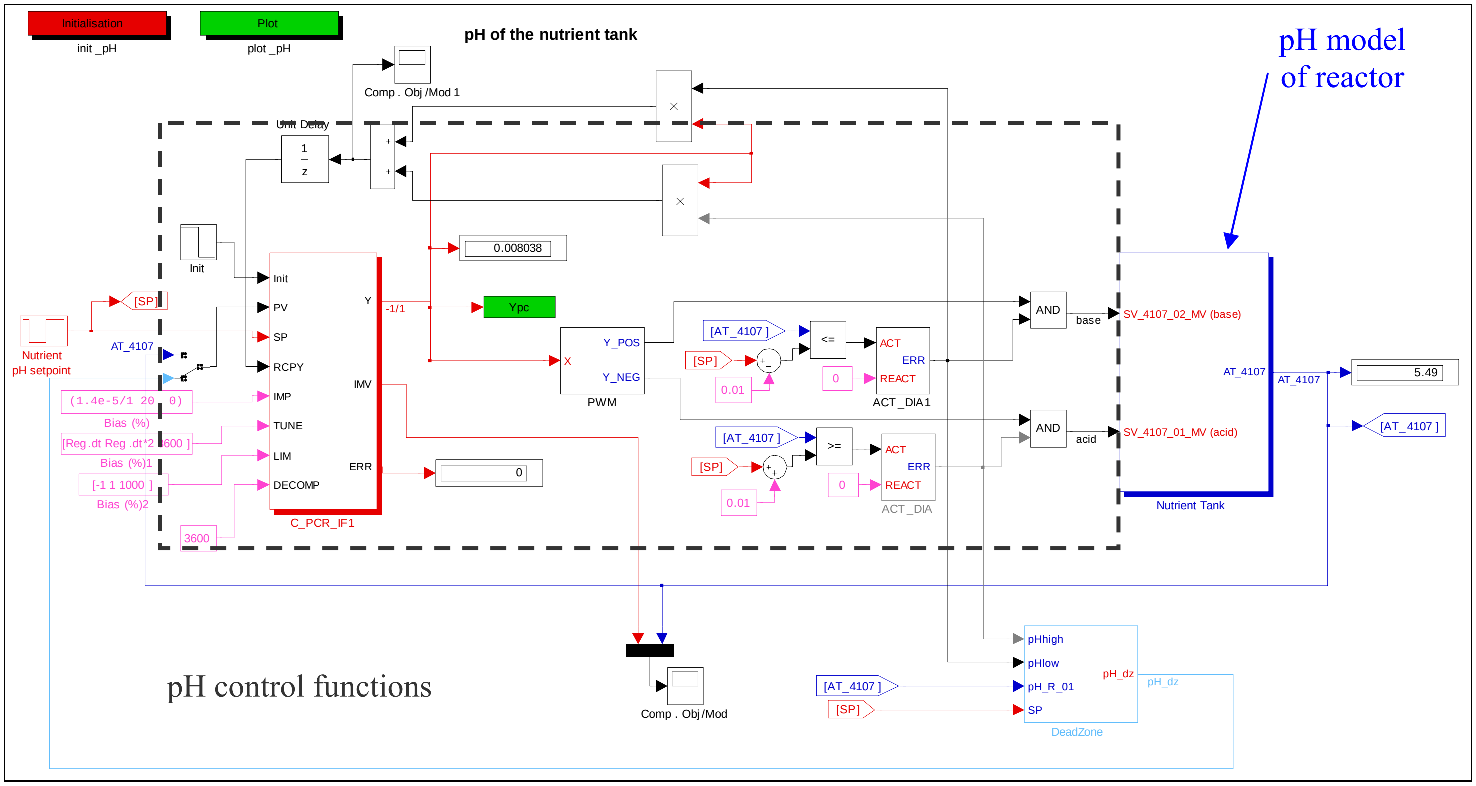


Figure 3: Simulator diagram dedicated to pH control

The simulator is made up of two parts:

- The first part replicates the control functions which are programmed in the PLC:
  - 1 PCR regulator
  - 1 PWM which steers the acid valve or the base valve
  - miscellaneous blocks to handle dead-zone
- The second part models the evolution of the pH with added base and acid:
  - The concentration c(t) of $[H^+]$ ions in tank is expressed from an elementary mass balance consideration:

$$\frac{dc(t)}{dt} = \frac{1}{V} \cdot \left[q_A(t).c_A + q_B(t).c_B \right] \text{ Where:}$$

– c_A : excess hydrogen ion concentration of the acid reagent (5 mol/L)

– c_B : excess hydrogen ion concentration of the base reagent (-5 mol/L)

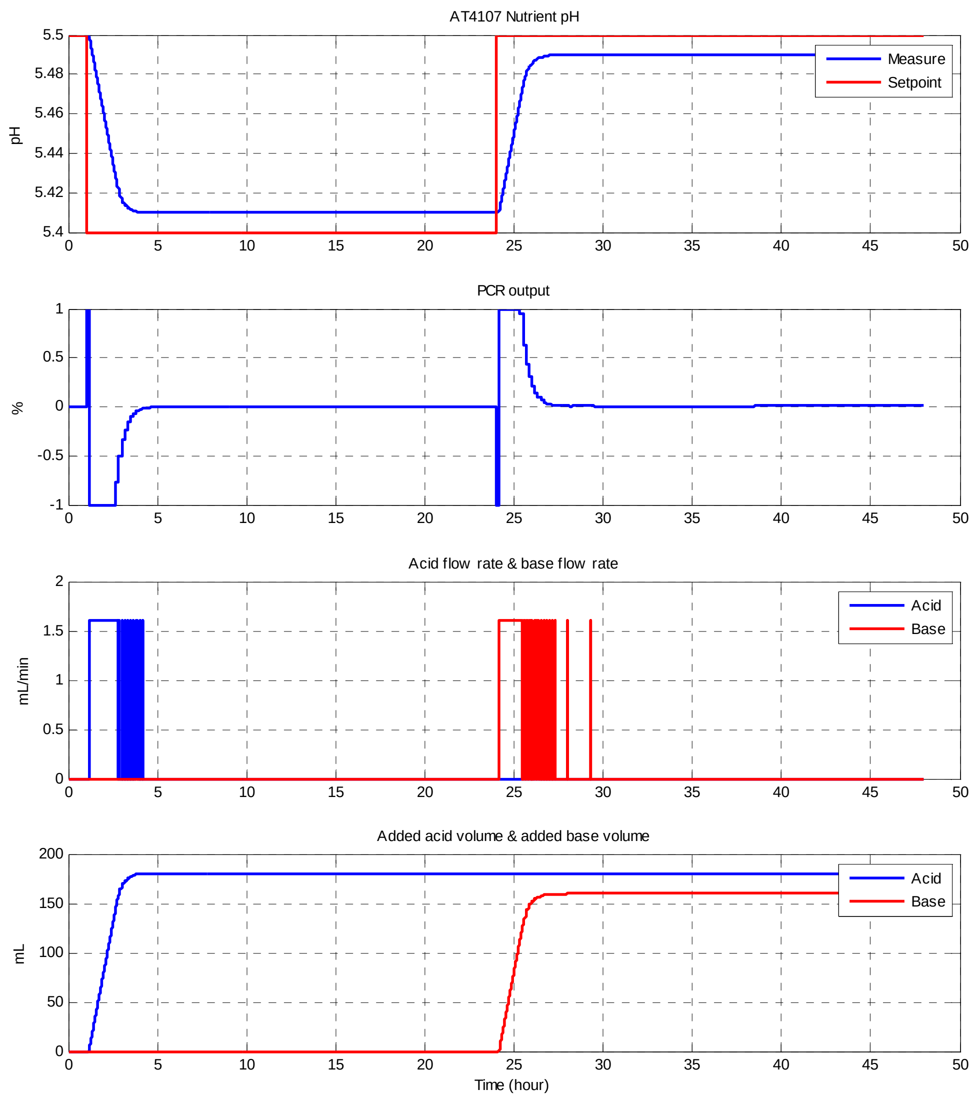
– q_A : flow rate of the acid reagent (L/s)

– q_B : flow rate of the base reagent (L/s)

– V : volume of the tank, considered constant (~ 100 L)

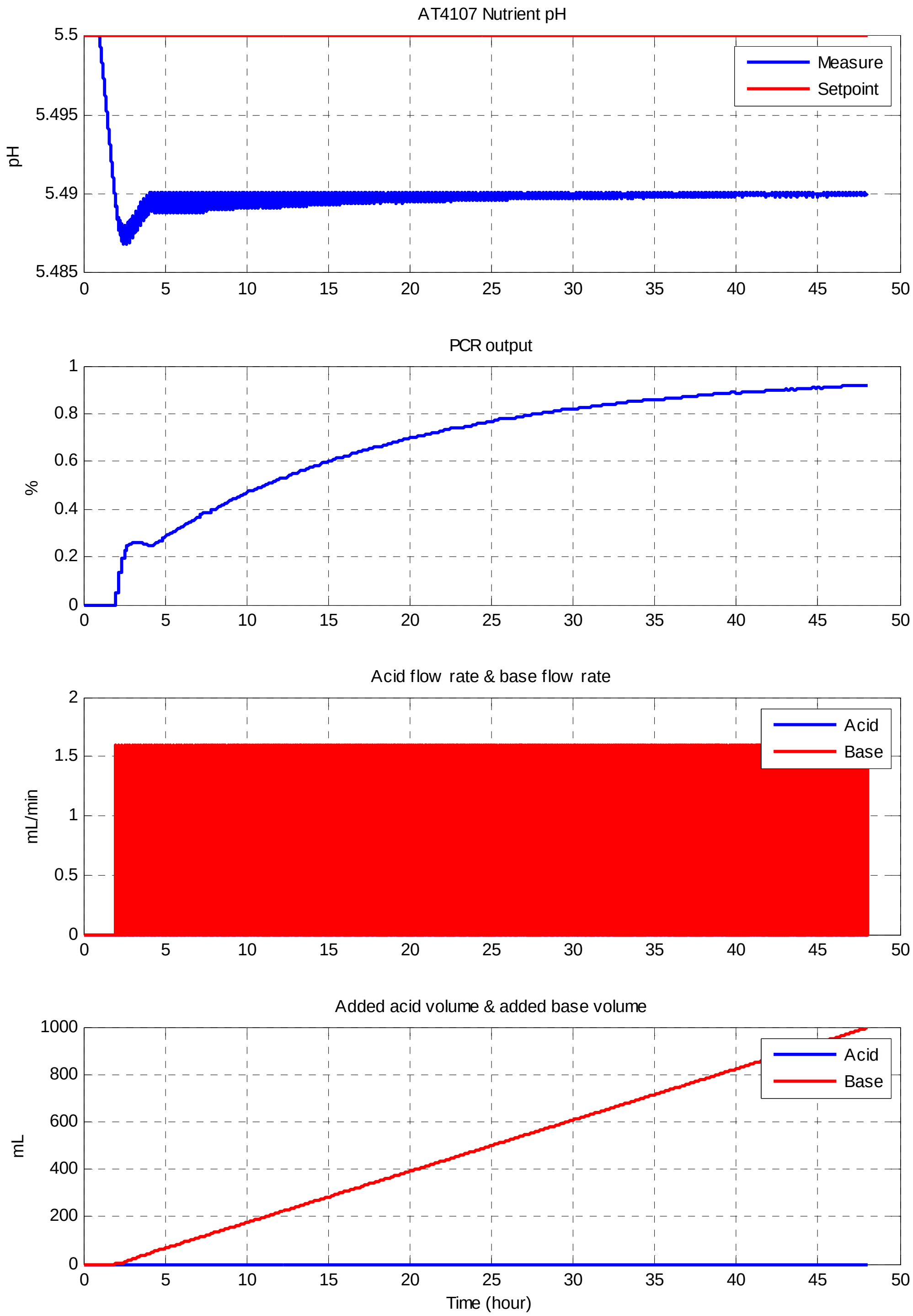
2.2.2.Simulation results

Changes of set-point are simulated from an initial pH equal to 5.5.



CL_4107 PH Control

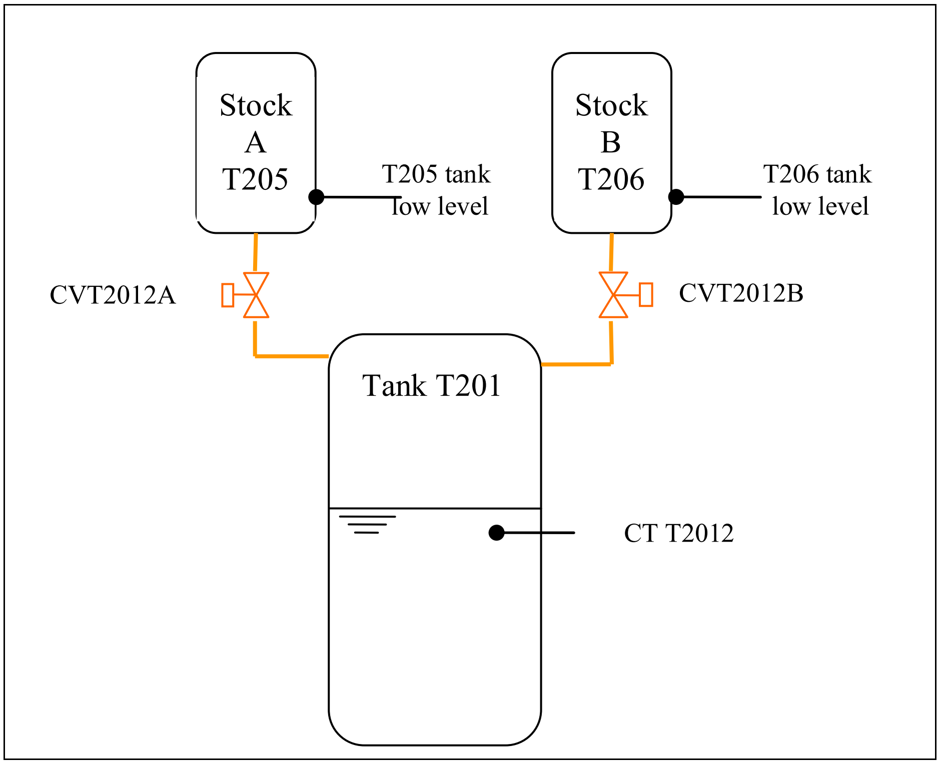
Second simulation represents an acidification of the nutrient tank, due to the plants.



CL_4107 PH Control

3. EC Control

Electrical Conductivity (EC) should be appropriate for the plant culture.
EC is usually around 1900 $\mu S.m^{-1}$



EC is regulated by means of two nutrient tanks (Tank A and B) od different electro conductivity

3.1. Control

3.1.1.1. *Specification*

- EC Set Point : 1900
  - 1850 < EC < 1950

3.1.1.2. *Control strategy*

- A fixed proportion between both tank.
- A predictive controller to control EC

- The control period is 10 min.
- An on-off control is used, by means of PWM (Pulse Width Modulators), whose maximum active times are 5 min. This prevents from continuously adding reagent.

The control period is 10 min, and the active time of the PWM is limited to 5 min: so

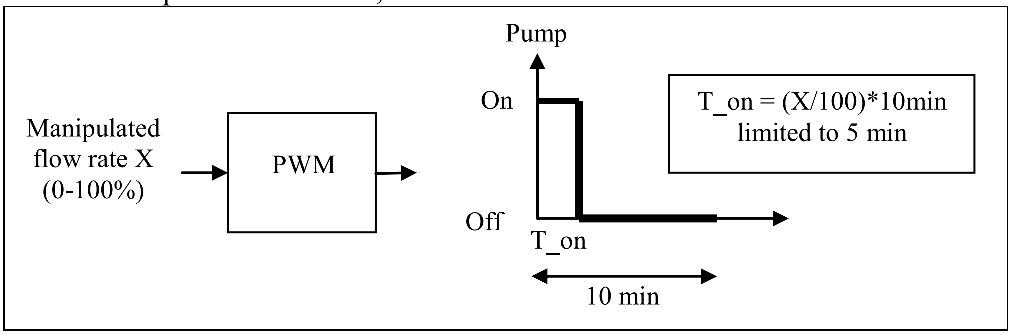


Figure 4: EC on-off control

3.2. Model

3.2.1.Structure, equations and parameters

The EC model of the bioreactor and its environment and control is developed with Simulink.

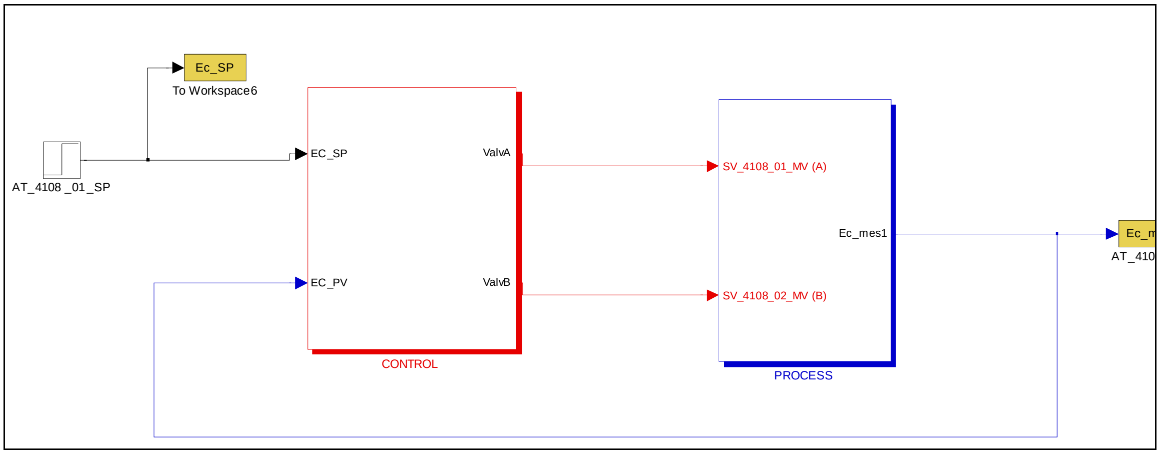


Figure 5 : Simulator Diagram dedicated to EC control

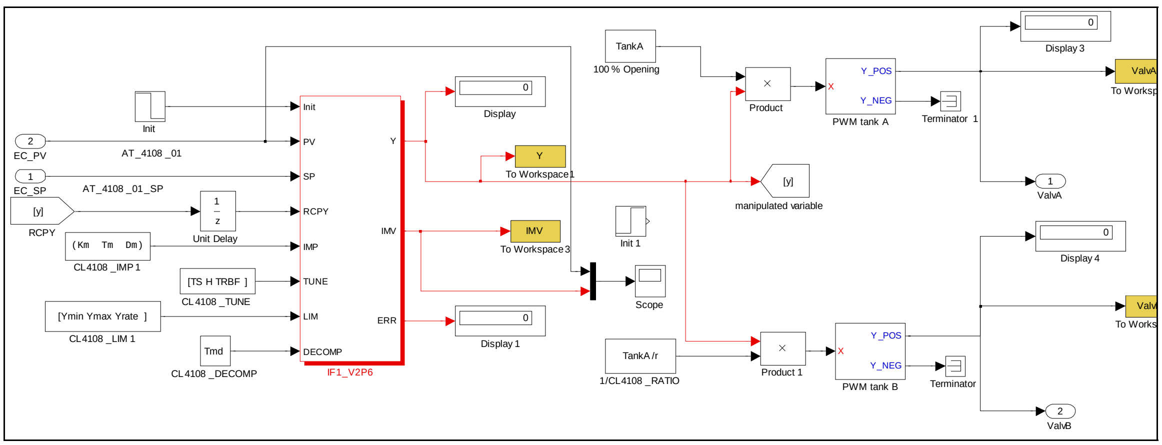


Figure 6 : EC Control

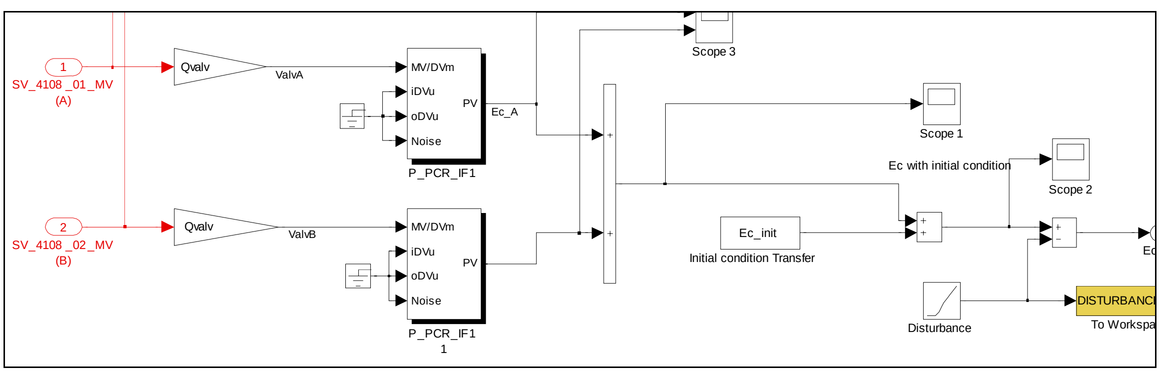


Figure 7 : EC Simulation

The simulator is made up of two parts:

- The first part replicates the control functions which are programmed in the PLC:
  - 1 PCR regulator
  - 2 PWM which steers the TankA valve and the TankB valve

- The second part models the evolution of the tank EC with added TankA and TankB:

$EC = EC + EC_A + EC_B - EC_{cons}$ where:
- EC_A : added EC from Tank A
- EC_B : added EC from Tank B
- EC_{cons} : consumption of EC by the plants

3.2.2. Simulation results

A change of set point is simulated from an initial EC equal to 1800 mS/m
A disturbance (EC_{cons}) is added at time = 2 hours.

4. CO2 control

4.1. Modelling of the process

The evolution of the CO2 concentration in the crop growing chamber (A500) can be represented by the schema bloc of the following Figure 4.1 :
Given :

- r_C : consumption of CO2 by the plants;
- u : input flow rate of CO2 from supply;
- V : total volume of A500 & A300;
- x : CO2 concentration of A500.

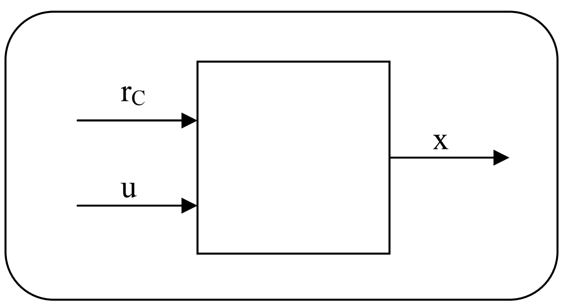


Figure 4.1 : Schema bloc of the process (CO2 concentration of A500)

The mass conservation of CO2 in the total volume of A500 & A300 implies :

$$V \cdot \dot{x} = r_C + u \qquad (2.1)$$

$\Rightarrow$ pure integrative process, without dynamic nor delay.

In order to control dynamically this process, a slight time constant τ is added. Then the expression of x becomes in Laplace transform :

$$x = \frac{G}{p} \cdot \frac{1}{1 + \tau \cdot p} \qquad (2.2)$$

with $G = \frac{1}{V}$ and τ set to an arbitrarily value of a few seconds.

4.2. Control

Such a process as (2.2) is controlled by a PCR_IF1 (Figure 4.2).

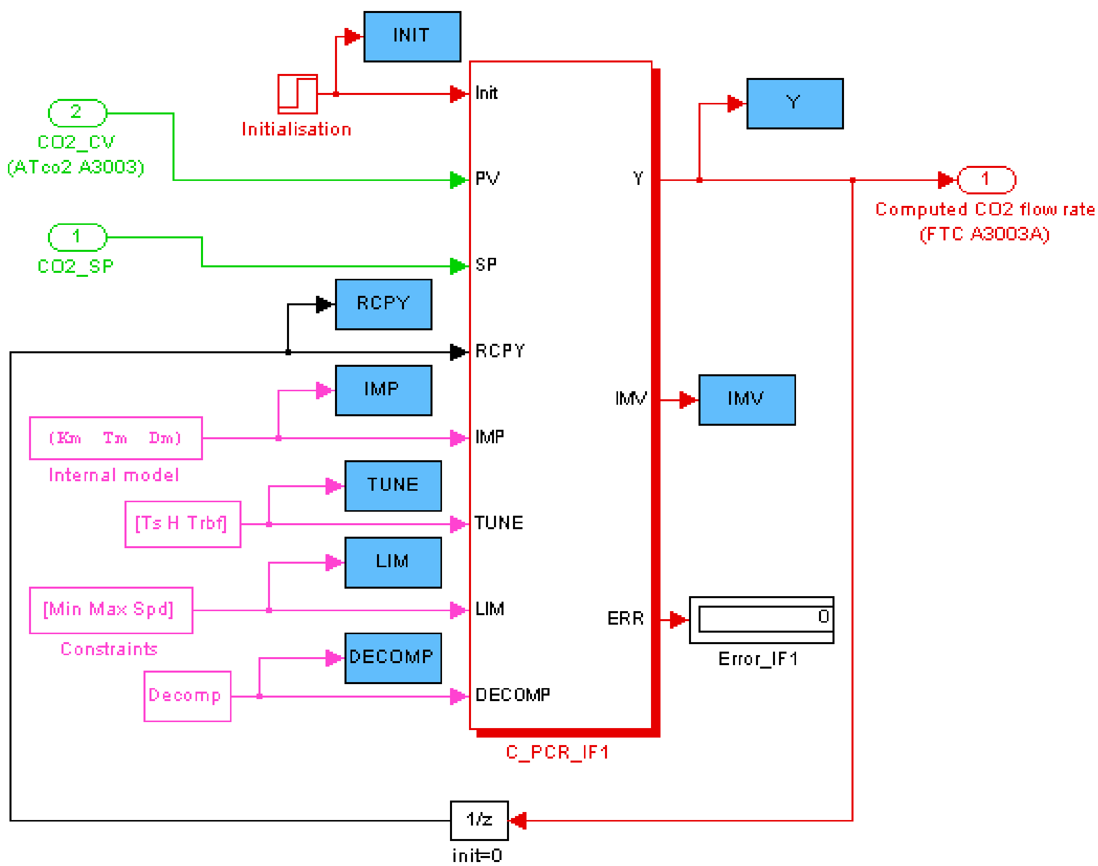


Figure 4.2 : Controller of CO2 concentration of A500

The parameters of the control are :

```
Ts = 0.1; % (s)
H = 1; % (s)
Trbf = 30* τ; % to reduce MV amplitude

Decomp = 30;
```

```
% Internal Model
Km = Kp;
Tm = Tp;
Dm = Dp;

% Constraints
Min = 0;
Max = 1e-3; % (NL/s) Arbitrary value
Spd = 1e4;
```

4.3. Test on simulator

The closed loop system is simulated by means of Simulink tools (Figure 4.3).

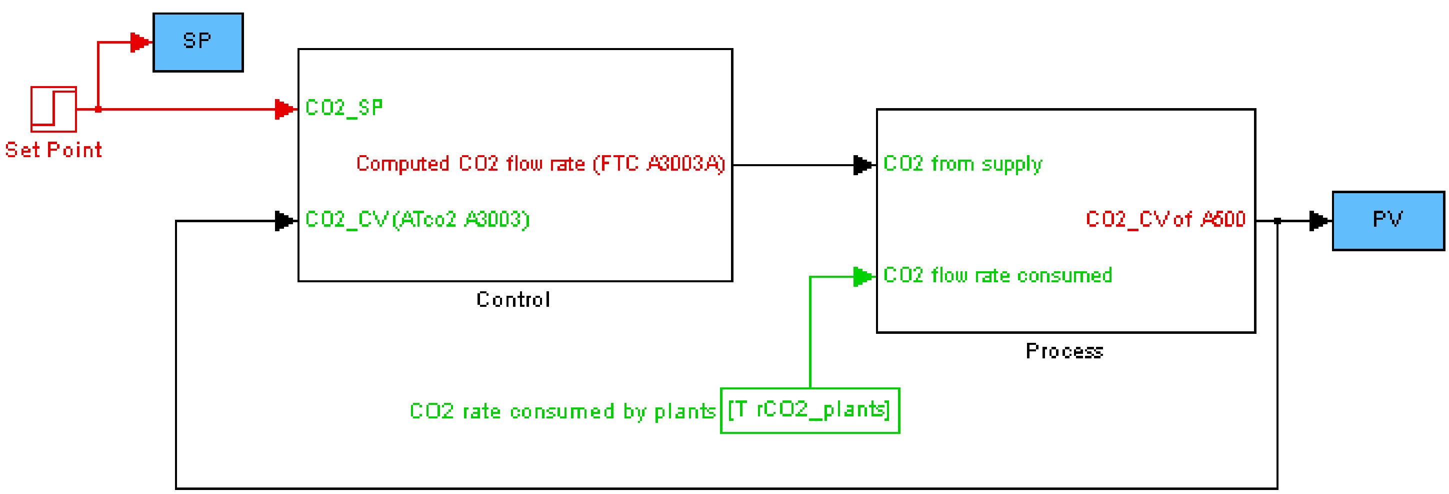


Figure 4.3 : Closed loop system

The control box of Figure 4.3 is detailed in the Figure 4.2 .

Figure 4.4 shows a CO2 setpoint step from 1000 to 1005 ppmv. The specified clrt is 100 s. The obtained one is 110 s because of the constraint Max on the input flow rate from supply. No overshoot. No oscillations.

The next Figure 4.5 shows the evolution of the CO2 concentration along a one day cycle : 10 hours of night where plants produce CO2 followed by 14 hours of day light. During the night, the control put the MV to 0 and the CO2 concentration increase. At t = 10 h, the plants begin to consume CO2 and the control maintains the MV to 0 as long as the CO2 concentration is above its setpoint. Then the control opens the valve from the CO2 supply so that the CV remains on its setpoint. No overshoot. No oscillations. Despite the high white noise on the CO2 produced or consumed by plants, the MV is not too noisy.

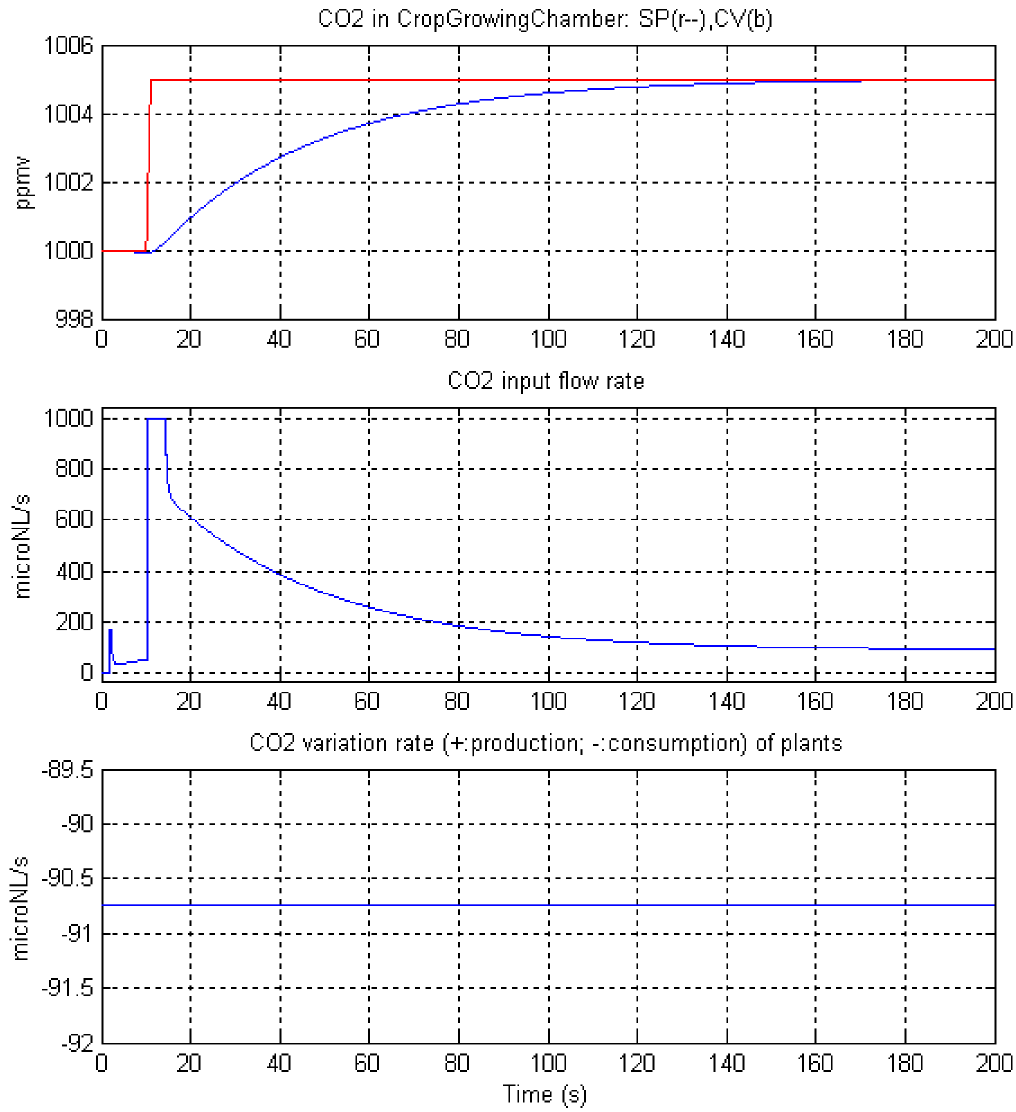


Figure 4.4 : CO2 setpoint step from 1000 to 1005 ppmv

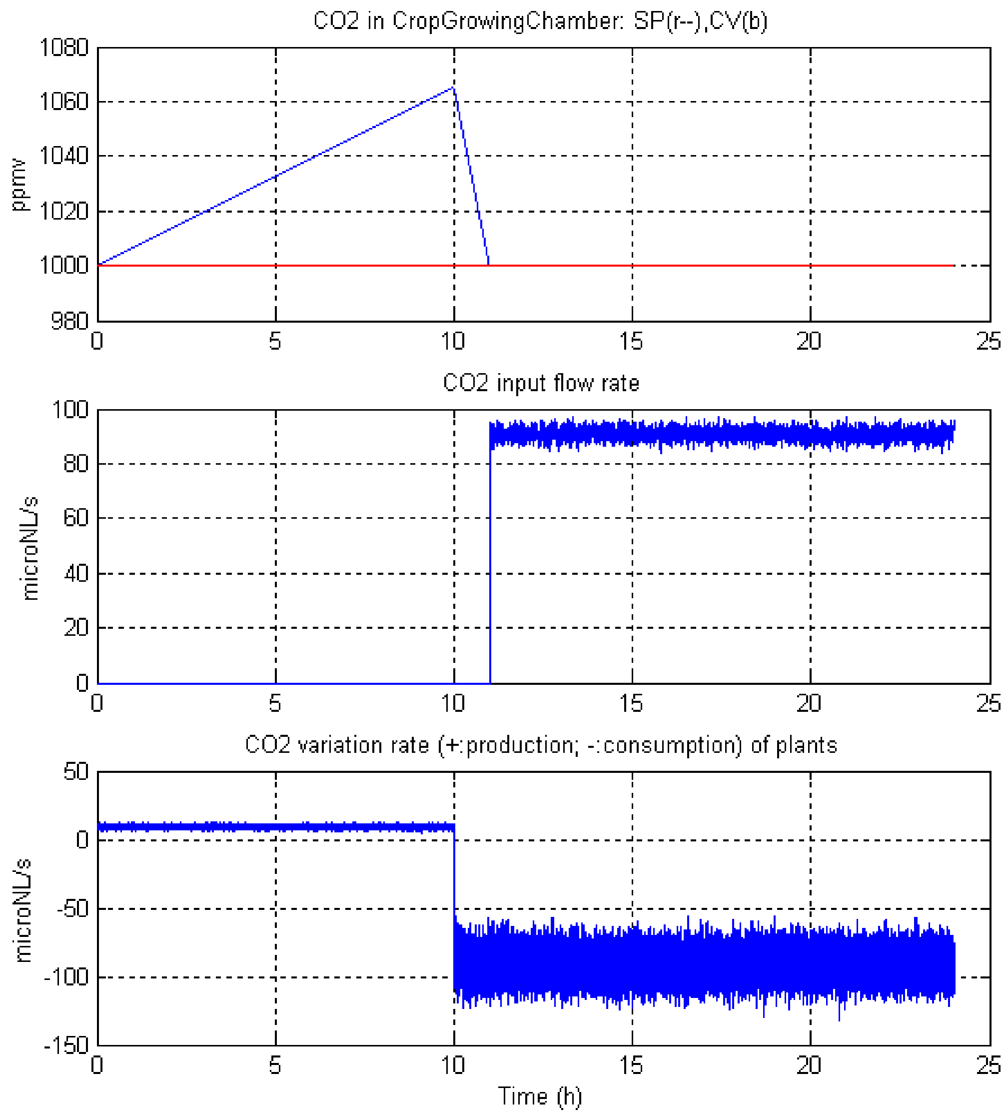


Figure 4.5 : Evolution of CO2 concentration along a one day cycle

5. Temperature and humidity controls

5.1. Modelling

5.1.1. Modelling of the HPC

Scheme of the PhiSim simulator.

5.1.2. Modelling of heat exchanger

5.1.2.1. *Definition*

This model applies to heat exchanger systems, where a temperature (Ts) has to be controlled using the utility fluid valve as manipulated variable (Figure 5.1).

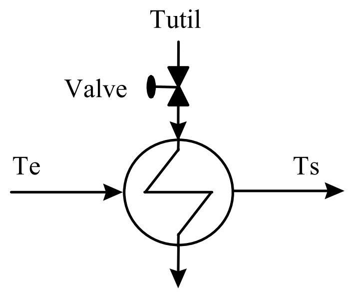


Figure 5.1 : Scheme of a heat exchanger

To identify this system, some signals are necessary: the outlet product temperature (Ts), the inlet product temperature (Te) and the utility valve between 0% and 100% or, which is equivalent, the flow rate. For the utility temperature, 2 options are available: either the temperature is recorded, or the user can fix it as a constant value.

5.1.2.2. *Representation*

In stationary behaviour, the system can be formulated as:

$$Ts = (1-\lambda)\cdot Te + \lambda \cdot Tutil \quad \text{with:} \qquad \lambda = f(valve) \tag{3.1}$$

This equation can be written in this way: $Ts - Te = \lambda \cdot (Tutil - Te)$

The system dynamic is inside the λ coefficient as follows:

$$\lambda = \frac{K.e^{-D.s}}{1+T.s}\cdot valve \tag{3.2}$$

The final equation is:

$$Ts - Te = \frac{K.e^{-D.s}}{1+T.s}\cdot valve \cdot (Tutil - Te) \tag{3.3}$$

Finally, it is a 1^{st} Order system with `[Ts-Te]` as the output signal, and `[valve.(Tutil-Te)]` as the input signal.

5.1.3. Modelling of RH

Given :

- r_w : water flow rate produced by evapo-transpiration of the plants;
- Q_w : water production flow rate at the cooler surface;
- Qa : volumetric flow rate of re-circulating air;
- T_a : Air temperature of the A500 (Crop Growing Chamber)
- T_{ac} : Air temperature at cooler output
- x : concentration of vapour water of the A500 at T_a;
- x_c : concentration of vapour water at cooler outlet at T_{ac};
- T_0 : absolute temperature at 0°C (T_0=273 K);
- R : constant of perfect gases.

It is noted that the volumetric flow rate of air, Q_a , is expressed under the normal conditions of temperature and pressure : T_0 & 1 atm. When the temperature of air is set to the absolute temperature T, the flow rate becomes $Q_a \cdot \frac{T}{T_0}$, the pressure being supposed unchanged at 1 atm.

The mass flow rates of vapour water at input & output of the A500 are :

- $-Q_a \cdot \frac{T_0 + T_a}{T_0} \cdot x$: output flux under 1 atm;
- $Q_a \cdot \frac{T_0 + T_{ac}}{T_0} \cdot x_c$: input flux from cooler output under 1 atm;
- r_w : input mass flow rate (due to the evapo-transpiration of the plants).

Then the mass balance of water in A500 implies :

$$V \cdot \dot{x} = -Q_a \cdot \frac{T_0 + T_a}{T_0} \cdot x + Q_a \cdot \frac{T_0 + T_{ac}}{T_0} \cdot x_c + r_w$$

$$\Leftrightarrow \quad \dot{x} = \frac{Q_a}{V} \cdot \frac{T_0 + T_a}{T_0} \cdot \left(-x + \frac{T_0 + T_{ac}}{T_0 + T_a} \cdot x_c + \frac{T_0}{Q_a \cdot (T_0 + T_a)} \cdot r_w \right) \qquad (3.4)$$

As long as there is no condensation in the cooler, x & x_c are bound by the following relation at constant pressure, deduced from the general relation of perfect gases :

$$x \cdot (T_0 + T_a) = x_c \cdot (T_0 + T_{ac}) \qquad (3.5)$$

When condensation occurs, x_c remains equal to the saturation concentration x_{sc} that is bound to the saturation pressure p_{sc} :

$$x_c = x_{sc} \quad \text{with} \quad x_{sc} = \frac{p_{sc}}{R \cdot (T_0 + T_{ac})} \qquad (3.6)$$

The condition of no condensation is given by the limit of x_c both in (3.5) & (3.6) :

$$x \cdot \frac{T_0 + T_a}{T_0 + T_{ac}} < x_{sc} \quad \Leftrightarrow \quad p_{sc} > x \cdot R \cdot (T_0 + T_a) \qquad (3.7)$$

So the expressions of x_c are :

$$x_c = x \cdot \frac{T_0 + T_a}{T_0 + T_{ac}} \quad \text{if} \quad p_{sc} > x \cdot R \cdot (T_0 + T_a) \quad \text{(no condensation)} \qquad (3.8)$$

$$x_c = \frac{p_{sc}}{R \cdot (T_0 + T_{ac})} \quad \text{if} \quad p_{sc} \le x \cdot R \cdot (T_0 + T_a) \quad \text{(condensation)} \qquad (3.9)$$

The water production of the cooler is the difference between the input & output vapour water flow rates at inlet & outlet of the cooler :

$$Q_w = Q_a \cdot \frac{T_0 + T_a}{T_0} \cdot x - Q_a \cdot \frac{T_0 + T_{ac}}{T_0} \cdot x_c \qquad (3.10)$$

It can be checked that when x_c follows relation (3.8) corresponding to the case of no water condensation, $Q_w = 0$ in (3.10). It confirms the fact that the cooler cannot add water.

The definition of the relative humidity R_H is :

$$R_H = \frac{p_p}{p_s}$$

with p_p : partial pressure of vapour water of A500
and p_s : saturation pressure at temperature T_a of A500

$$\Rightarrow R_H = \frac{x \cdot R \cdot (T_0 + T_a)}{p_s} \qquad (3.11)$$

Dynamic of the transfer T_{ac} → R_H :

The dynamic of T_a and $p_s = f(T_a)$ are identical. So, from (3.11), the dynamic of R_H is the same as the one of x.

Now from (3.4) the time constant of the transfer x_c → x is : $\theta = \frac{V}{Q_a} \cdot \frac{T_0}{T_0 + T_a}$

Moreover from(3.9), when there is condensation, x_c is statically bound to T_{ac} .
So the time constant of the transfer T_{ac} → R_H is also θ. And as the mean value of Ta is 18 °C, θ can be expressed as a constant :

$$\theta = \frac{V}{Q_a} \cdot \frac{273}{291} \qquad (3.12)$$

Static gain of the transfers T_a → R_H & T_{ac} → R_H :

Note : the static expression of a variable is represented with the index ∞ (infinite).

From (3.4) the static expression of x is :

$$x_\infty = A \cdot (T_0 + T_{ac\infty}) \cdot x_{c\infty} + B \cdot r_{w\infty} \tag{3.13}$$

with $A = \dfrac{1}{T_0 + T_{a\infty}}$ & $B = \dfrac{1}{Q_a} \cdot \dfrac{T_0}{T_0 + T_{a\infty}}$

The static expression of R_H is :

$$R_{H\infty} = \frac{x_\infty \cdot R \cdot (T_0 + T_{a\infty})}{p_{s\infty}}$$

$$\Rightarrow R_{H\infty} = \frac{R \cdot (T_0 + T_{a\infty})}{p_{s\infty}} \cdot \left(A \cdot (T_0 + T_{ac\infty}) \cdot x_{c\infty} + B \cdot r_{w\infty}\right)$$

The disturbance r_w being not measured, the only transfer $x_c \rightarrow R_H$ is interesting for the control and the static expression of R_H can be reduced to :

$$\Rightarrow R_{H\infty} = \frac{R}{p_{s\infty}} \cdot (T_0 + T_{ac\infty}) \cdot x_{c\infty} \tag{3.14}$$

At this point, 2 cases must be considered.

<u>Case 1 :</u>

There is condensation : (3.9) $\Rightarrow x_{c\infty} \cdot (T_0 + T_{ac\infty}) = \dfrac{p_{sc\infty}}{R}$

$$\Rightarrow R_{H\infty} = \frac{p_{sc\infty}}{p_{s\infty}} \tag{3.15}$$

According to the general Clapeyron expression of p_{sat} : $Ln \dfrac{p_{sat}}{p_{100}} = C \cdot \left(\dfrac{1}{T_{100}} - \dfrac{1}{T}\right)$

$$\Rightarrow R_{H\infty} = \exp\left(C \cdot \left(\frac{1}{T_0 + T_{a\infty}} - \frac{1}{T_0 + T_{ac\infty}}\right)\right)$$

where C is detailed below.

<u>Case 2 :</u>

There is no condensation : (3.8) $x_c = x \cdot \dfrac{T_0 + T_a}{T_0 + T_{ac}}$

$$\Rightarrow R_{H\infty} = \frac{x_\infty \cdot R \cdot (T_0 + T_{a\infty})}{p_{s\infty}} \quad \text{independent of } T_{ac\infty}. \tag{3.16}$$

Important remark : As T_{ac} is the manipulated variable of the RH control, relation (3.16) implies that **RH is uncontrollable when there is no condensation**.

The incremental gain of R_H versus the input T_a & T_{ac}, in case of condensation, deduced from relation (3.15) is shown in Figure 5.2.

<u>Remark 2 :</u> Expression of the **condition of no condensation**:
From (3.7) & (3.11) the condition of no condensation can be re-written :

$$p_{sc} > R_H \cdot p_s \tag{3.17}$$

where $p_{sc} = f(T_{ac})$ & $p_s = f(T_a)$ via Clapeyron formula or Mollier diagram.
and R_H is the measurement of relative humidity in A500.
This relation is true at any moment with the assumption that there is no transport delay from the outlet of A500 to the outlet of the cooler.
In case of transport delay δ, the condition of no condensation (3.17) becomes function of time t and delay δ :

$$p_{sc}(t) > R_H \cdot p_s(t-\delta) \tag{3.18}$$

<u>Expression of C in the Clapeyron formula</u> :

$$C = \frac{M \cdot L_v}{R}$$

M = 0.018 kg/mol : molar mass of water;
Lv = 2.26 10^6 J/kg : vapour heat (? chaleur latente de vaporisation);
R = 8.31447 J/K/mol : constant of perfect gas;
T_{100} = 373 K : ebullition temperature of water under 1 atm;
p_{100} = 1013 mbar = 1 atm;
p_{sat} : saturation pressure.

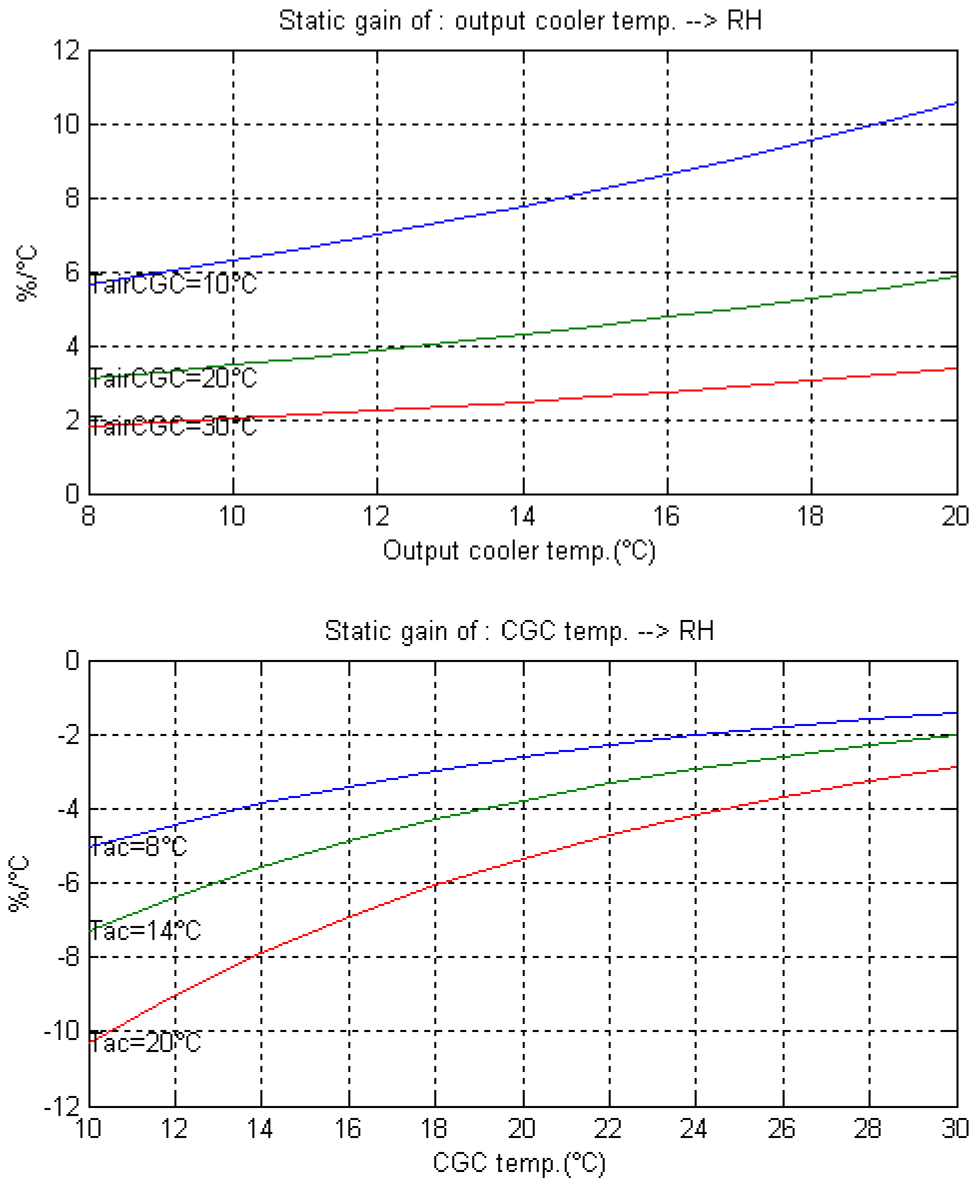


Figure 5.2 : Static gain (incremental gain) of RH versus T_a & T_{ac}

5.2. Identification

5.2.1. Identification related to the heater coil

Identification is done according to the model of section 5.1.2.
The system to be identified is (recall of relation (3.3)) :

$$Ts - Te = \frac{K.e^{-D.s}}{1+T.s} \cdot valve \cdot (Tutil - Te)$$

where :

- $Ts = T_a$;
- $Te = T_{ac}$;
- valve = hot water flow rate ;
- Tutil = temperature of hot water.

The gain K & time constant T depend on amplitude of the input. The following results (Figure 5.3 & Figure 5.4 & Table 5.1) are obtained for hot water flow rate steps of 0.003 kg/s & 0.1 kg/s, respectively and for a constant chilled water flow rate of 0.056 kg/s and no evapo-transpiration flow rate.

The identified results are gathered in the following table :

Hot water flow rate (kg/s)	**0.003**	**0.1**
Gain K (s/kg)	4.5	2.8
Time constant T (s) (approximate value)	15	3
Delay D (s)	0	0

Table 5.1 : Identification of the heater coil system

In these conditions, the air temperature increase of A500 is 1.4 & 18 °C, respectively.
The next figures (Figure 5.5 & Figure 5.6) show the behaviour of the main variables of HPC in response to the steps of hot water flow rate.

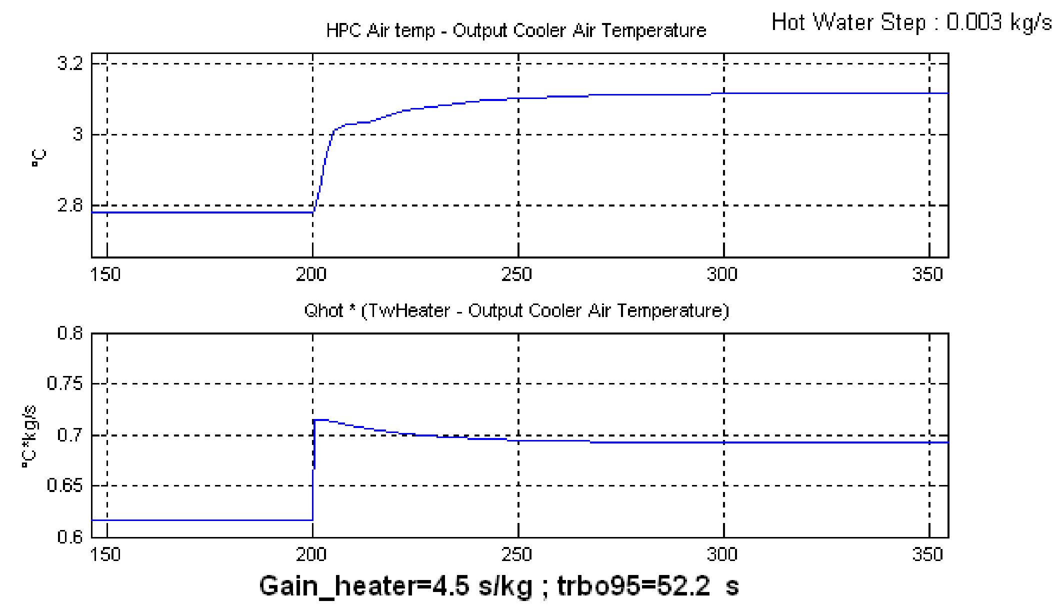


Figure 5.3 : Response of the system to input excitation for a hot water flow rate step of 0.003 kg/h

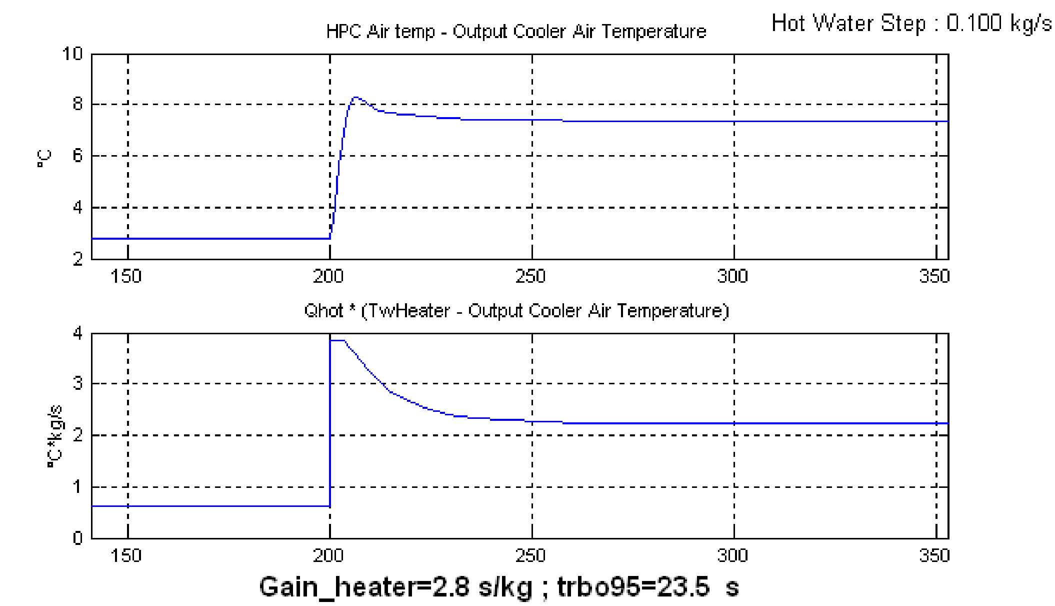


Figure 5.4 : Response of the system to input excitation for a hot water flow rate step of 0.1 kg/h

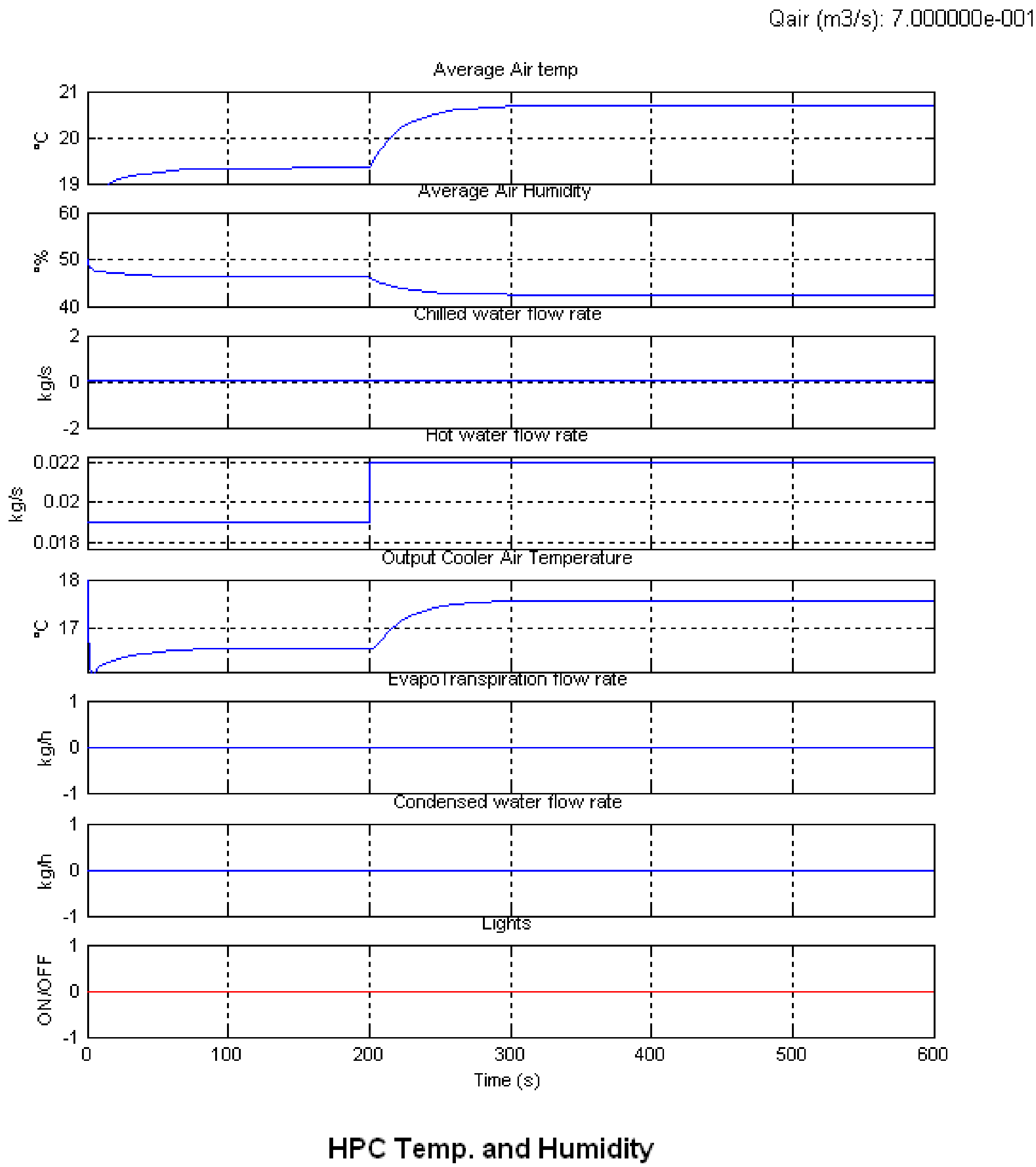


Figure 5.5 : Main variables of HPC for a hot water flow rate step of 0.003 kg/h

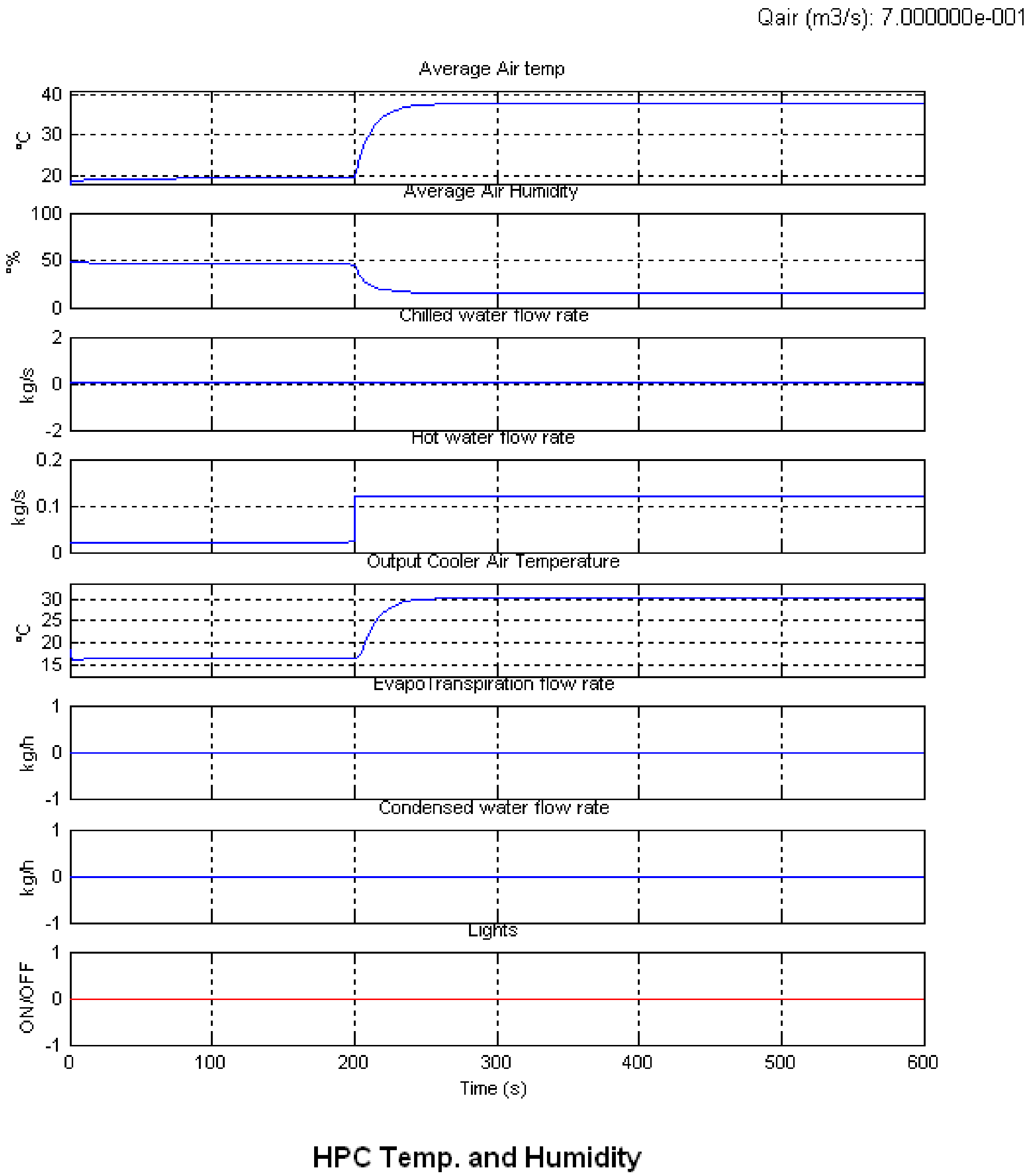


Figure 5.6 : Main variables of HPC for a hot water flow rate step of 0.1 kg/h

5.2.2. Identification related to the chilled coil

Identification is done according to the model of section 5.1.2.
The system to be identified is (recall of relation (3.3)) :

$$Ts - Te = \frac{K.e^{-D.s}}{1+T.s} \cdot valve \cdot (Tutil - Te)$$

where :

- $Ts = T_{ac}$;
- $Te = T_a$;
- valve = chilled water flow rate ;
- Tutil = temperature of chilled water.

The gains & open loop response time depend on amplitude of the input.
The following results (Figure 5.7 & Figure 5.8 & Table 5.2) are obtained for chilled water flow rate steps of 0.003 kg/s & 0.2 kg/s, respectively and for a constant hot water flow rate of 0.019 kg/s and no evapo-transpiration flow rate.

The identified results are gathered in the following table :

Chilled water flow rate (kg/s)	**0.003**	**0.2**
Gain K (s/kg)	4.0	1.0
Time constant T (s) (approximate value)	2	2
Delay D (s)	0	0

Table 5.2 : Identification of the cooler coil system

The air temperature decrease of A500 is 0.4 & 6 °C, respectively.
The next figures (Figure 5.9 & Figure 5.10) show the behaviour of the main variables of HPC in response to the steps of chilled water flow rate.

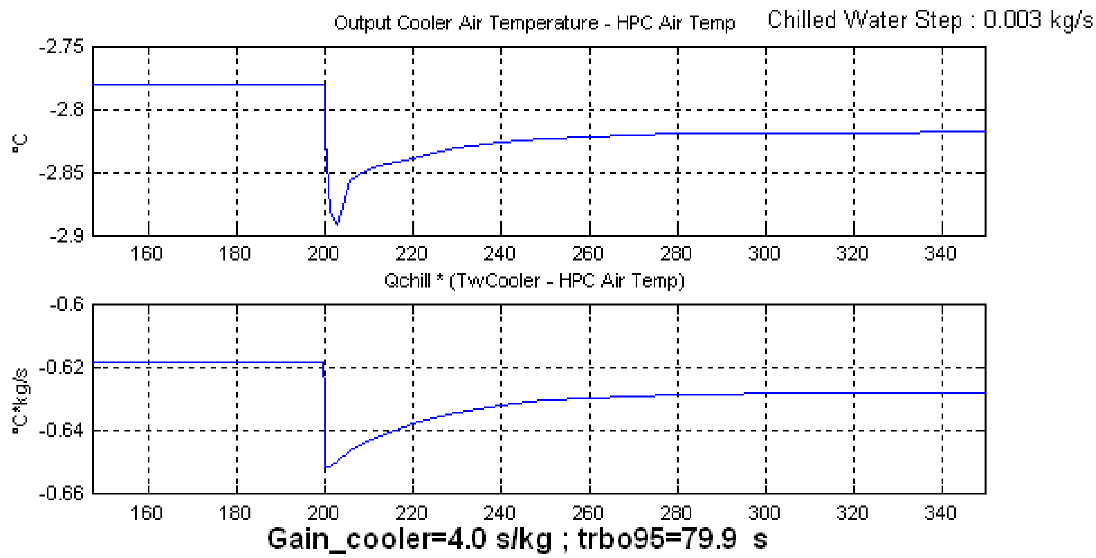


Figure 5.7 : Response of the system to input excitation for a chilled water flow rate step of 0.003 kg/h

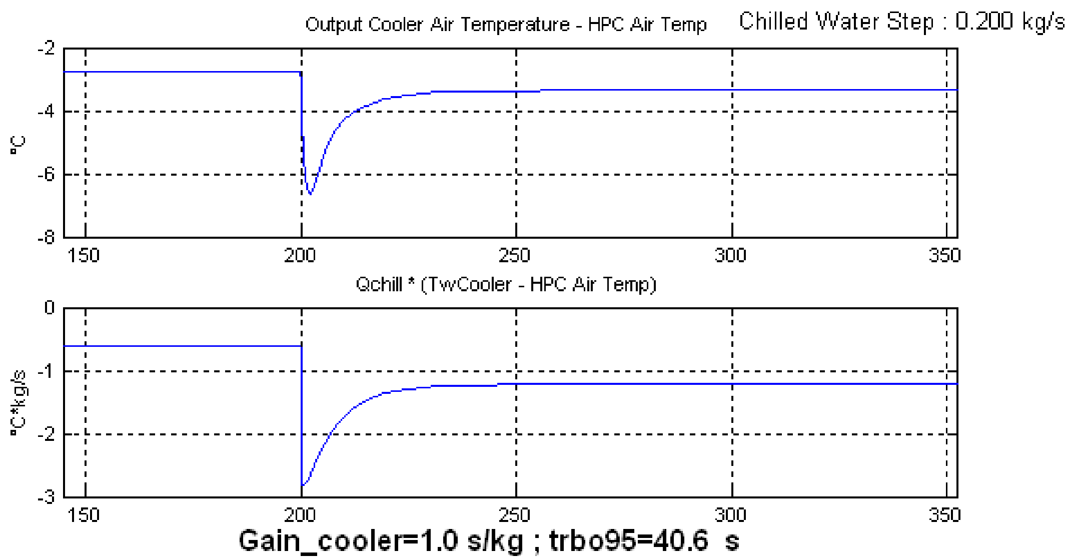


Figure 5.8 : Response of the system to input excitation for a chilled water flow rate step of 0.2 kg/h

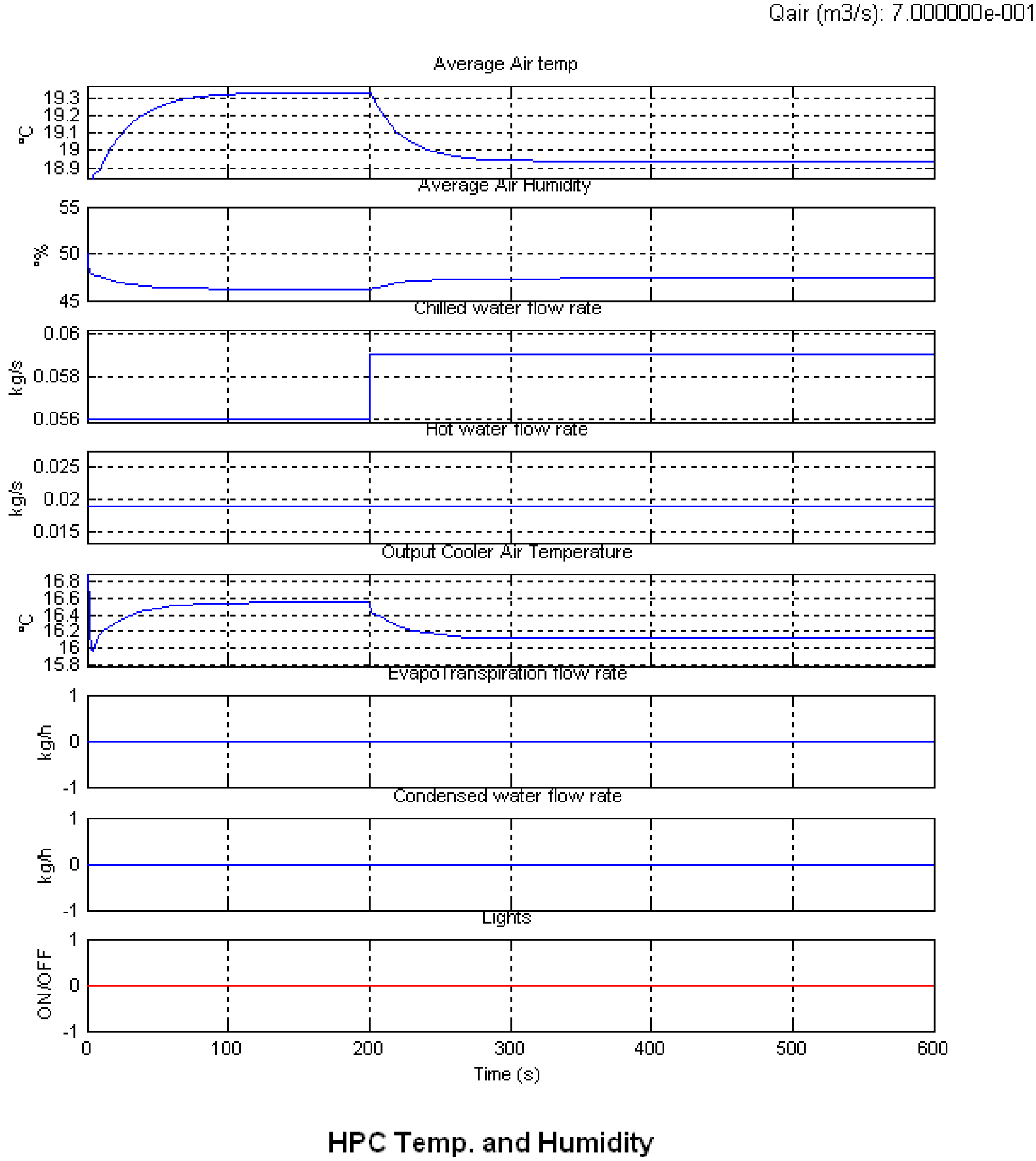


Figure 5.9 : Main variables of HPC for a chilled water flow rate step of 0.003 kg/h

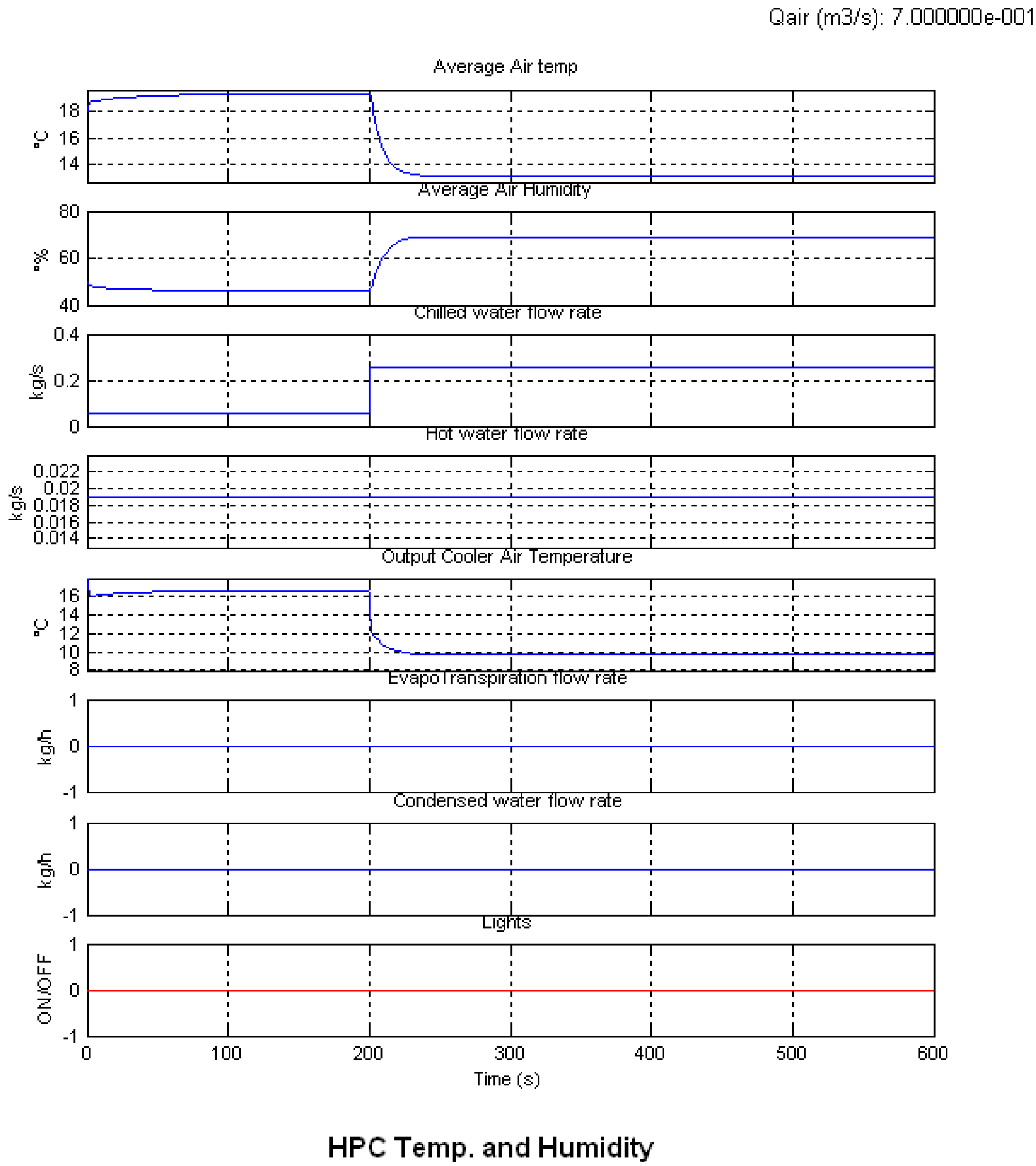


Figure 5.10 : Main variables of HPC for a chilled water flow rate step of 0.2 kg/h

5.2.3. Identification of AirOutputCoolerTemp_SP → RH

The control of RH is done by means of a cascade of 2 controllers : the slave controller is in charge of the temperature of air at cooler outlet whose setpoint is computed by the master controller in charge of RH control.
So the transfer to be identified is the one between the setpoint of the Air Output Cooler Temperature and RH.
The gain and time constant of this transfer depend on the amplitude of the input step. The identification has been done for 2 values of set point step : -1 & -2.5 °C.

For both excitations (Figure 5.11 & Figure 5.13), the response of RH is non minimal de-phasing. Moreover the first one (Figure 5.11) is over-tensed.

The identified results are gathered in the following table :

Temp. setpoint step (°C)	**-1**	**-2.5**
Gain K (%/°C)	4.3	4.0
Time constant T (s) (approximate value)	18	21
Delay D (s)	8	8

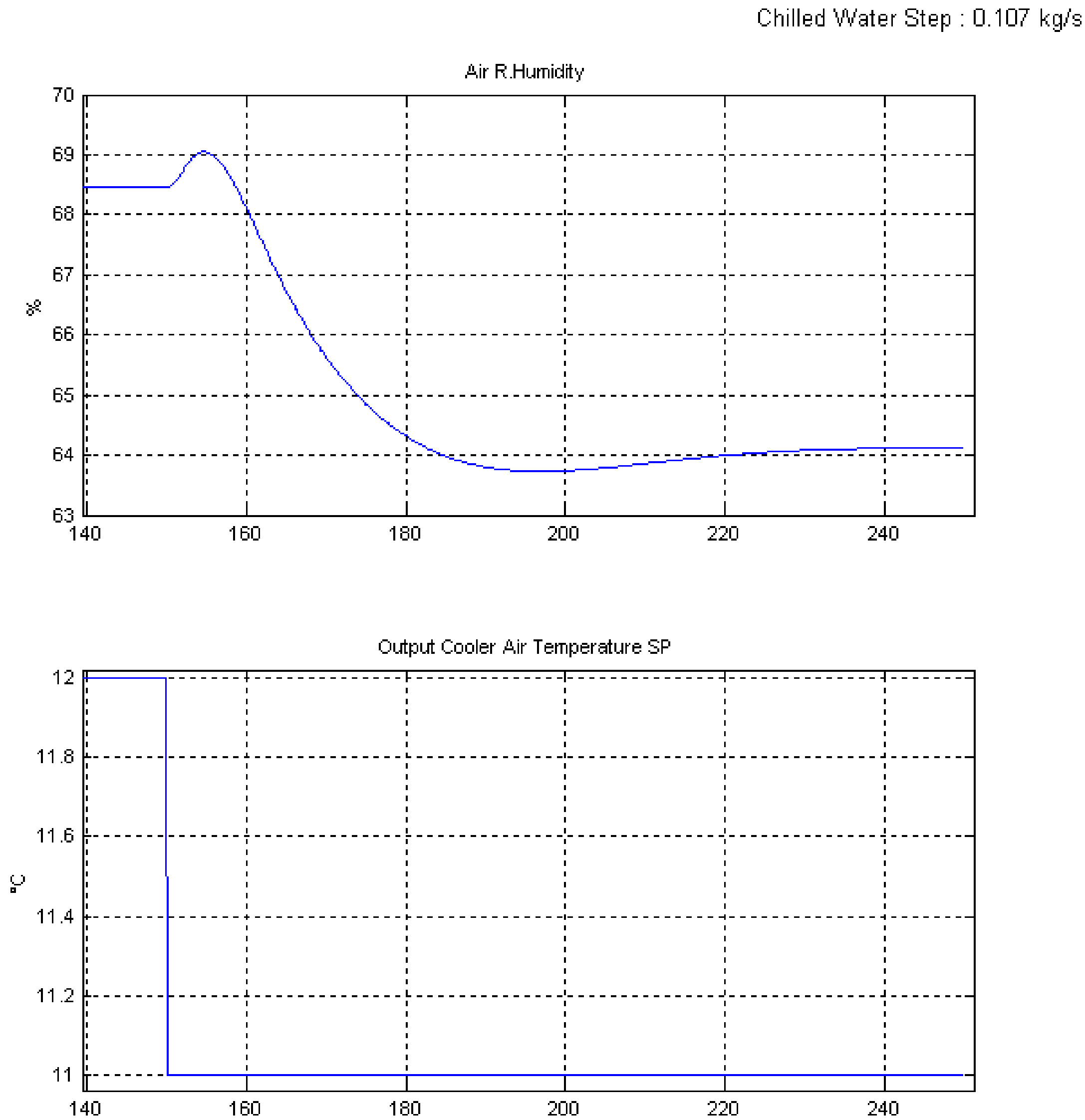
Table 5.3 : Identification of the RH transfer

Theoretical study (Figure 5.2) suggests that the gain can reach the value of 10 %/°C .

The next figures (Figure 5.12 & Figure 5.14) show the behaviour of the main variables of HPC in response to the steps of temperature setpoint.

Remark for identification on the pilot plant :
Static gain : Identification is not necessary. The value can be the maximum of the theoretical domain plotted in upper graph of Figure 5.2 and restricted to the pilot plant. For example : if the temperature of A500 (called CGC in this figure) varies between 20 & 30 °C and if the temperature of air at cooler outlet varies between 8 & 16 °C, then the gain is about 5 %/°C.
Time constant and delay (if any) : They cannot be obtained from modelling. Identification is necessary. The protocol of test consists in steps of temperature set point while evaporating water at a constant flow rate (as constant as possible). Several amplitudes of step around several steady state points of temperature and RH of A500.

Temperature setpoint step = -1 °C (Chilled water flow rate variation = 0.107 kg/s)



Gain_RH=4.3 percent/°C ; trbo95=63.0 s

Figure 5.11 : Response of RH to a temperature setpoint step of -1 °C

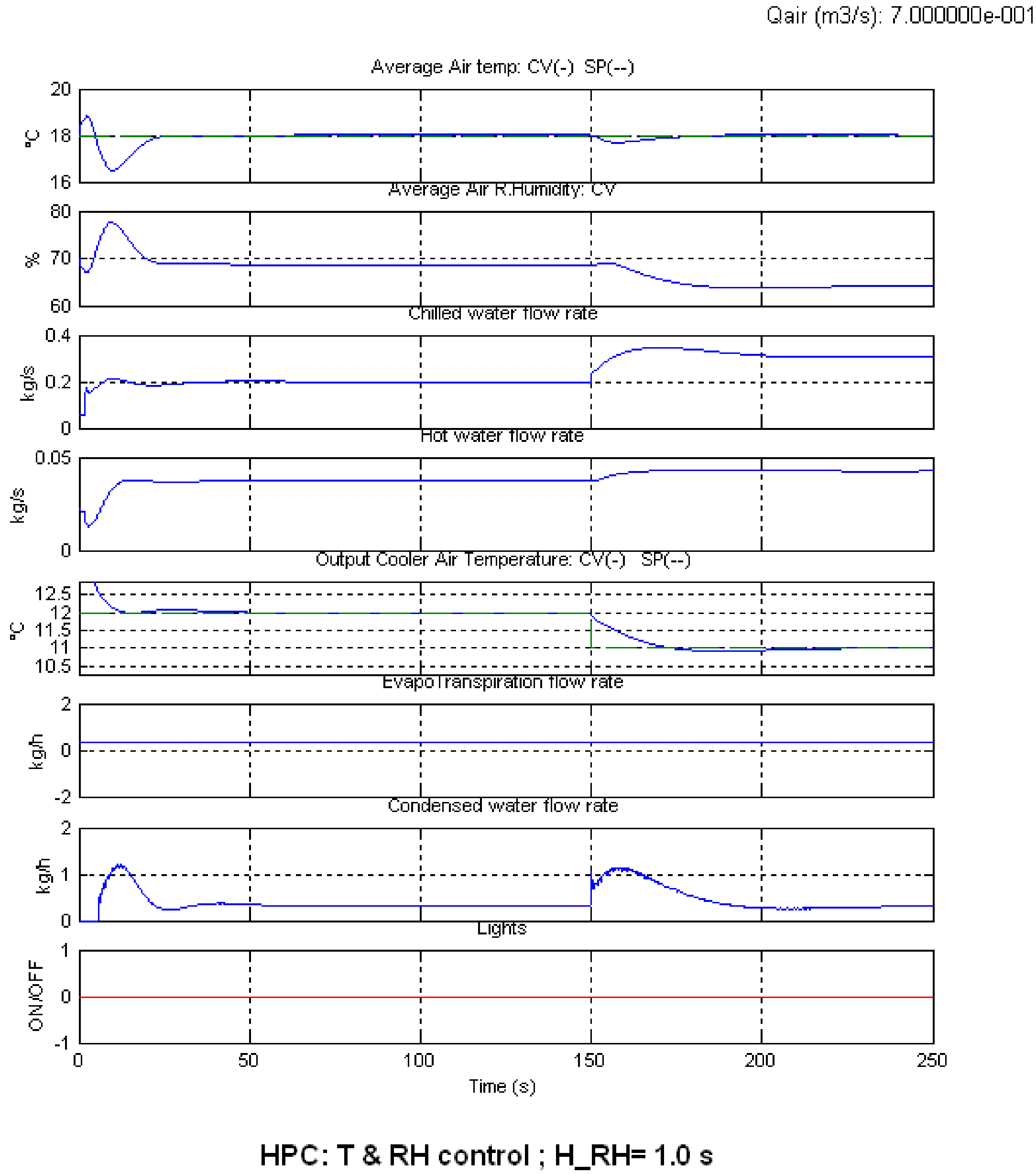


Figure 5.12 : Main variables of HPC for a temperature step of – 1 °C

Temperature setpoint step = -2.5 °C (Chilled water flow rate variation = 0.974 kg/s)

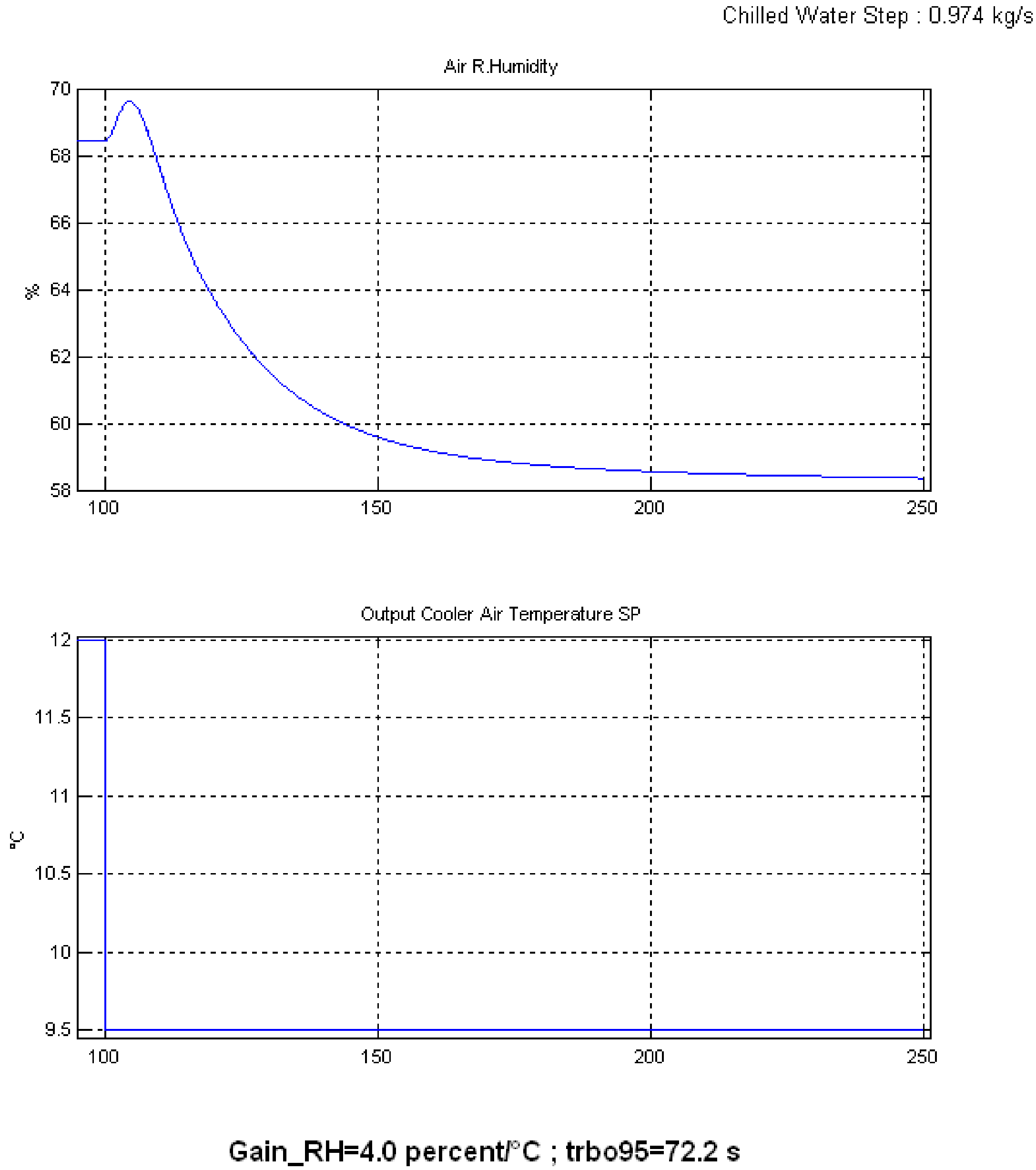


Figure 5.13 : Response of RH to a temperature setpoint step of -2.5 °C

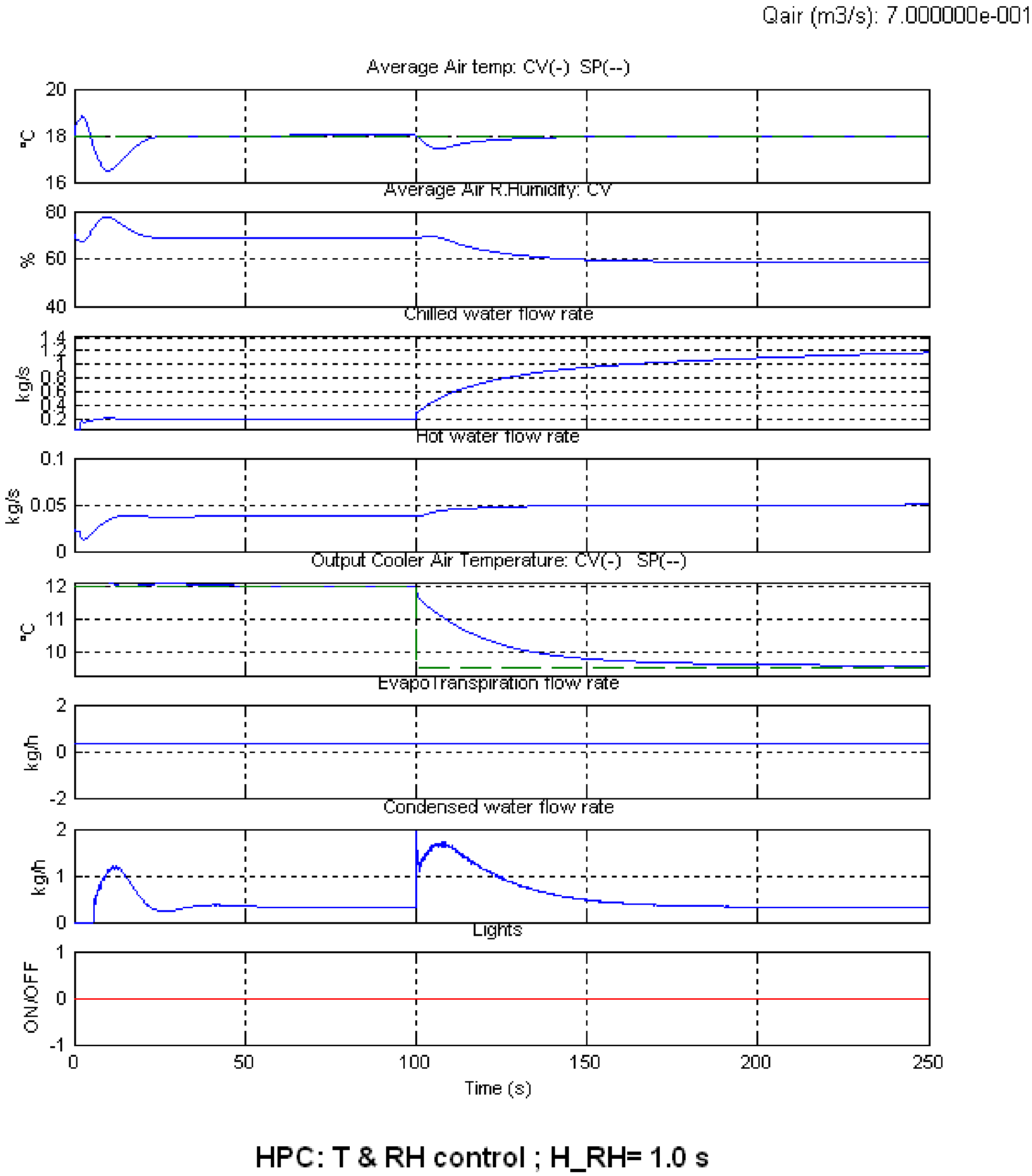


Figure 5.14 : Main variables of HPC for a temperature step of – 2.5 °C

5.3. Architecture & parameters of the control

5.3.1. Architecture

The control of Temperature and RH is composed of (Figure 5.15) :

- the controller 'Tair_PCR' in charge of control of temperature 'A500_AirTemp_CV' by means of 'HotFlowRate', taking into account of the disturbance 'OutCoolerAirTemp_CV';
- a cascade of Master controller 'RH_PCR' and of Slave controller 'Tair_OutCooler_PCR' taking into account of the disturbance A500_AirTemp'. The cascade is in charge of control of 'RH_CV' by means of 'ChilledFlowRate'.

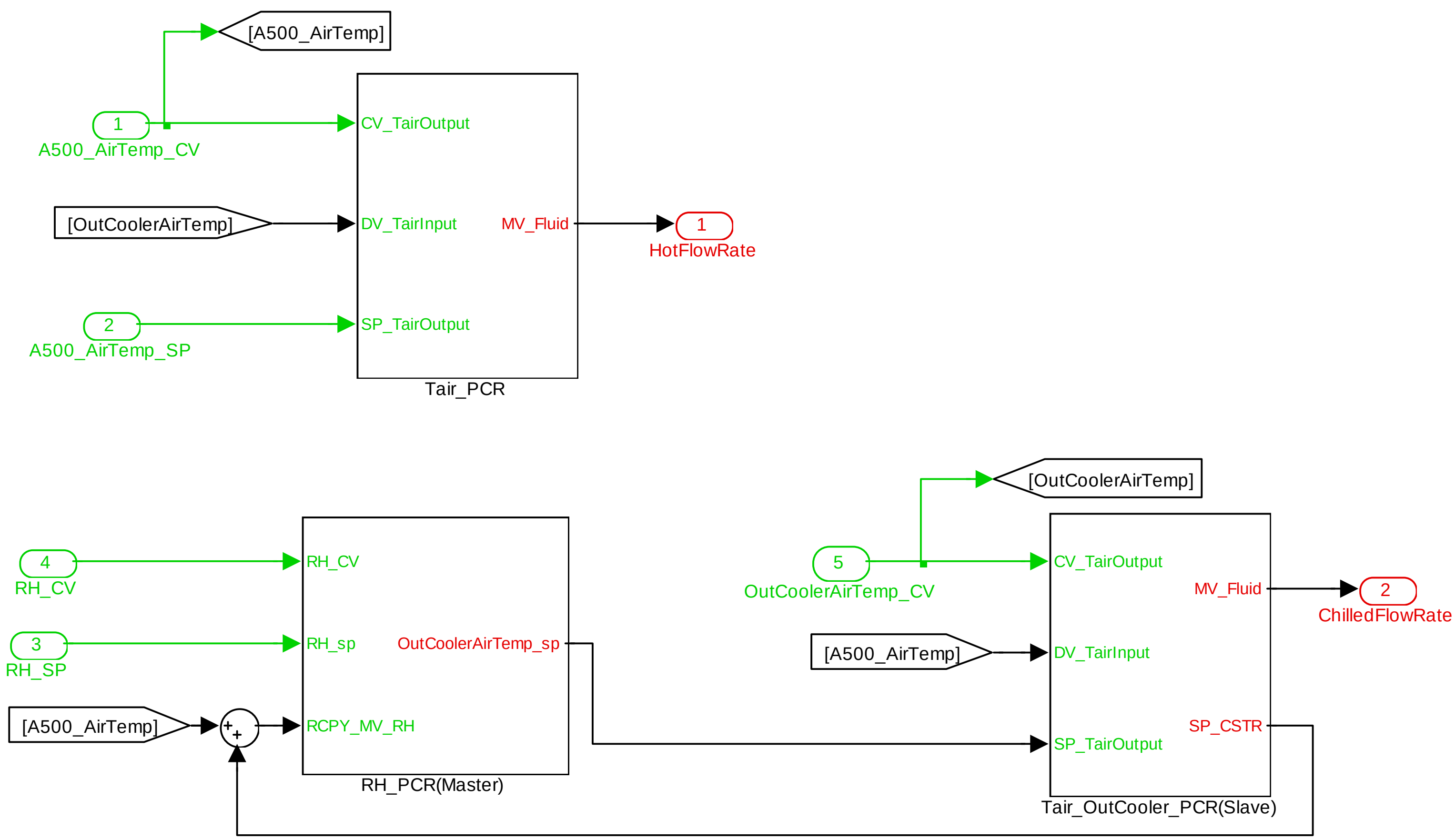


Figure 5.15 : Control architecture of Temperature & RH

5.3.2. Parameters of the controllers

```
%-----------------------------------------------------
%Control 1 : A500 Air Temperature Control by PCR
%-----------------------------------------------------
H_Ta = Ts; % H=TS : 1st order

% Internal Model
Km_Ta = 4; % 3; % (s/kg) Identification result (mean value between 2.8 & 4.5 s/kg))
Tm_Ta = 5; % (s) Identification result (mean value between 3 & 15 s)
Dm_Ta = 0;

% Zone
Zone_Ta = 0;
Trbf_Lo_Ta = 3*Tm_Ta;
Trbf_Hi_Ta = 10*Trbf_Lo_Ta;

% Constraints
Min_Ta = 0;
Max_Ta = (B302.Thot - B301.Tcold) * B302.Qhot; % (°C*kg/s)
Spd_Ta = 5; % (°C*kg/s/s)

%-----------------------------------------------------
%Control 2 : Out Cooler Air Temperature Control by PCR
%-----------------------------------------------------
H_Tac = Ts; % H=TS : 1st order

% Internal Model
Km_Tac = 3; % (s/kg) Identification result (mean value between 1 & 4 s/kg)
Tm_Tac = 2; % (s) Identification result
Dm_Tac = 0;

% Zone
Zone_Tac = 0;
Trbf_Lo_Tac = 3*Tm_Tac;
Trbf_Hi_Tac = 10*Trbf_Lo_Tac;

% Constraints
Min_Tac = (B301.Tcold - B302.Thot) * B301.Qcold; % (°C*kg/s)
Max_Tac = 0; % (°C*kg/s)
Spd_Tac = 5; % (°C*kg/s/s)

%-----------------------------------------------------
%Control 3 : A500 Air RH Control by PCR
%-----------------------------------------------------
H_RH = 5*Ts; %

% Internal Model
Km_RH = 10; % (%/°C)  Theoretical result (max value); Gain if condensation
Tm_RH = 20; % (s) Identification result (min value)
Dm_RH = 8; % (s) Identification result of non minimal de-phasing

% Zone
Zone_RH = 0;
Trbf_Lo_RH = 3*Tm_RH;
Trbf_Hi_RH = 100*Trbf_Lo_RH;

% Constraints
Min_RH = B301.Tcold; % (°C)
Max_RH = 30; % (°C)
Spd_RH = 200; % no constrain
```

5.4. Test of control (on simulator)

5.4.1. Control of air temperature alone without RH control

The evapo-transpiration flow rate is constant. A temperature setpoint step is done at t = 75 s. The closed response time is 20 s (specified one is 15 s) with an overshoot of 20 %. A step of chilled water flow rate of 0.2 kg/s (rather big value) is applied at t = 150 s. It implies a deviation on air temperature of maximum equal to -1.5 °C.

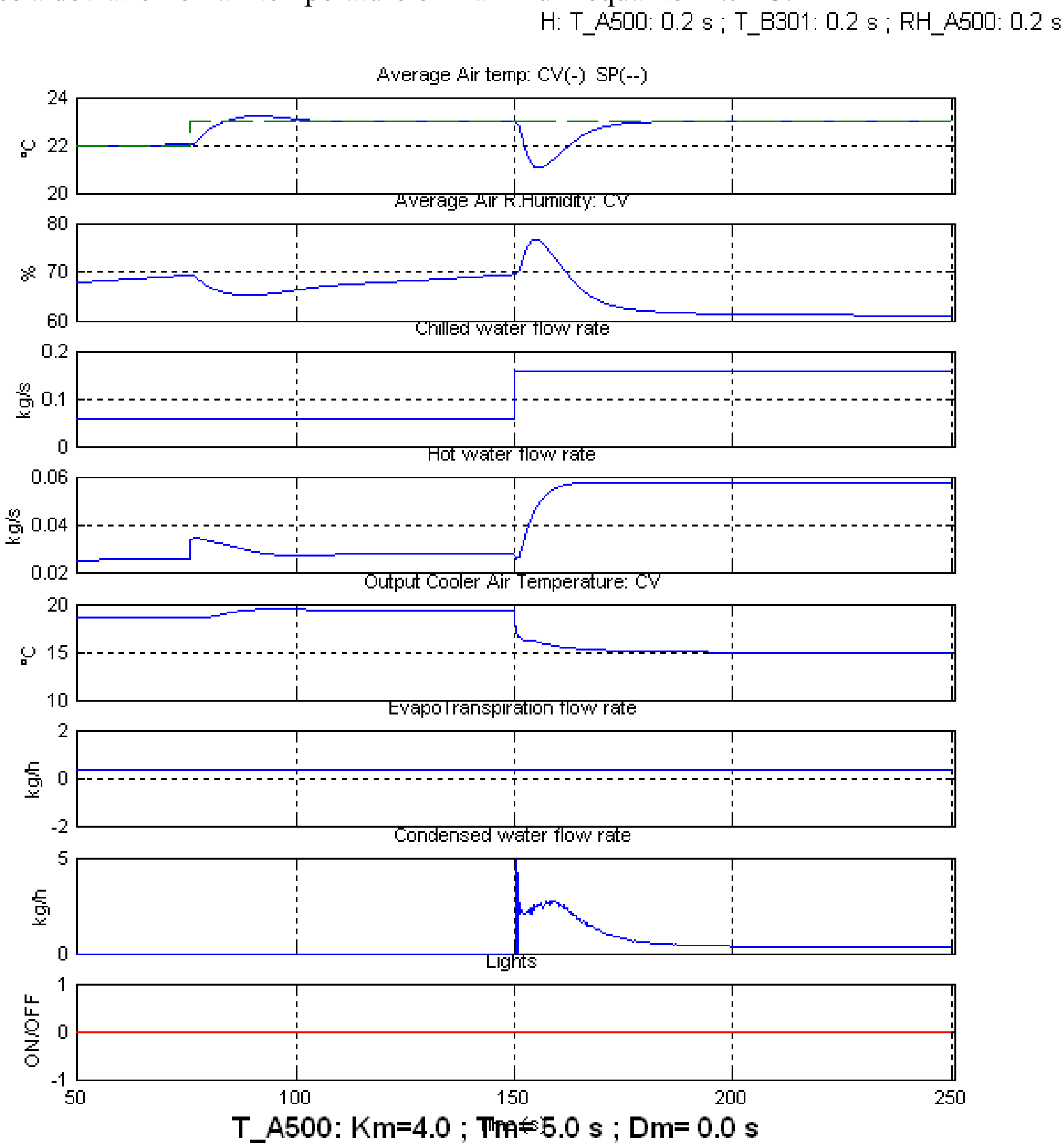


Figure 5.16 : Control of air temperature without RH control

5.4.2. Step of outlet cooler air temperature setpoint without RH control

The air setpoint is set to a constant value (22 °C) and the evapo-transpiration flow rate is constant. A step of 3 °C is applied to the outlet cooler air temperature setpoint at t = 100 s. The closed response time is 10 s (specified one is 6 s) with no overshoot.

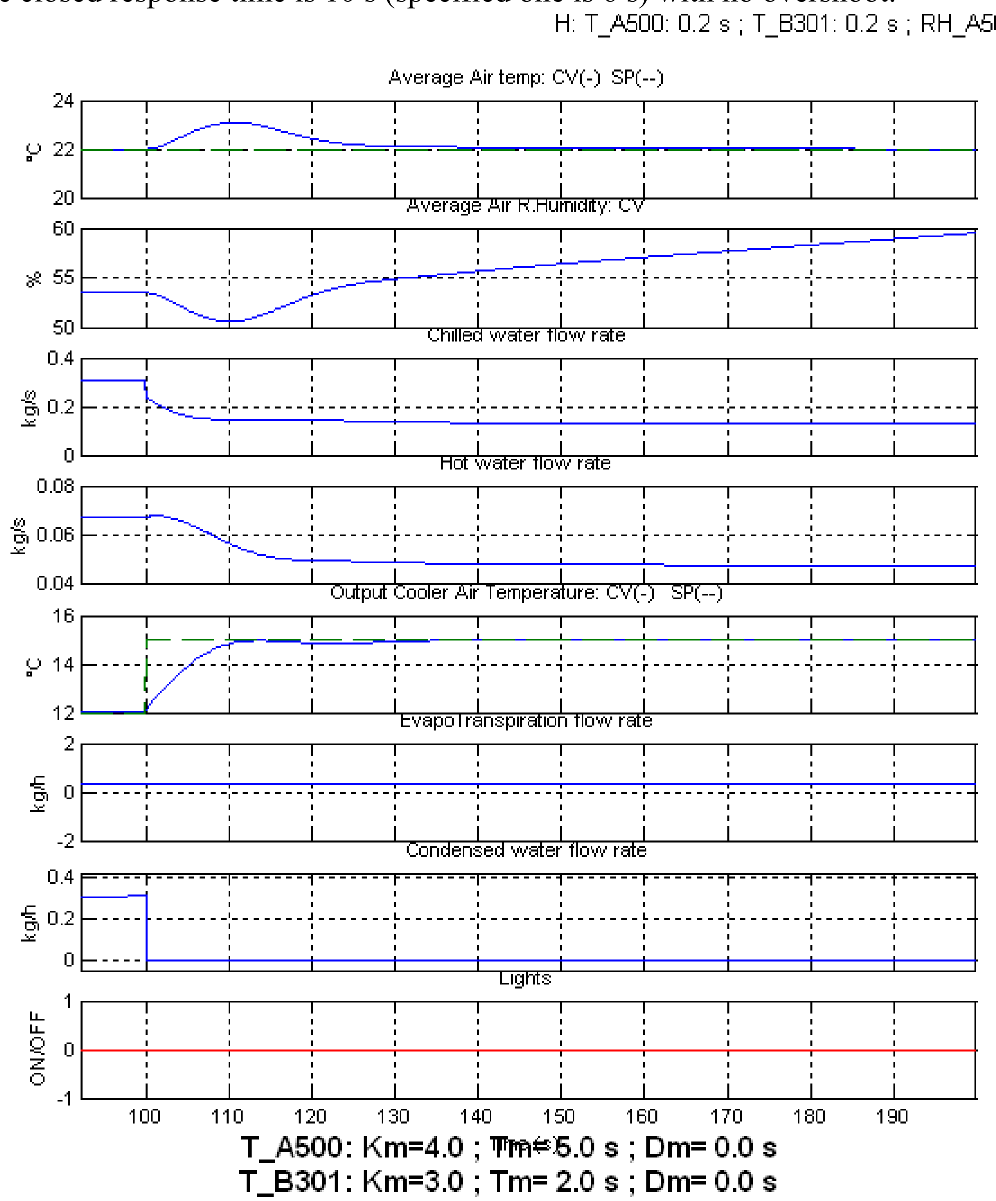


Figure 5.17 : Step of outlet cooler air temperature setpoint without RH control

5.4.3. Temperature set point steps with constant RH setpoint

The behaviour is not symmetrical. The overshoot is 20 % for a positive set point step and 40 % for a negative one. During 50 s after the step, RH moves away from its set point with a maximum distance of 5 % absolute. Temperature oscillations are induced by RH oscillations.

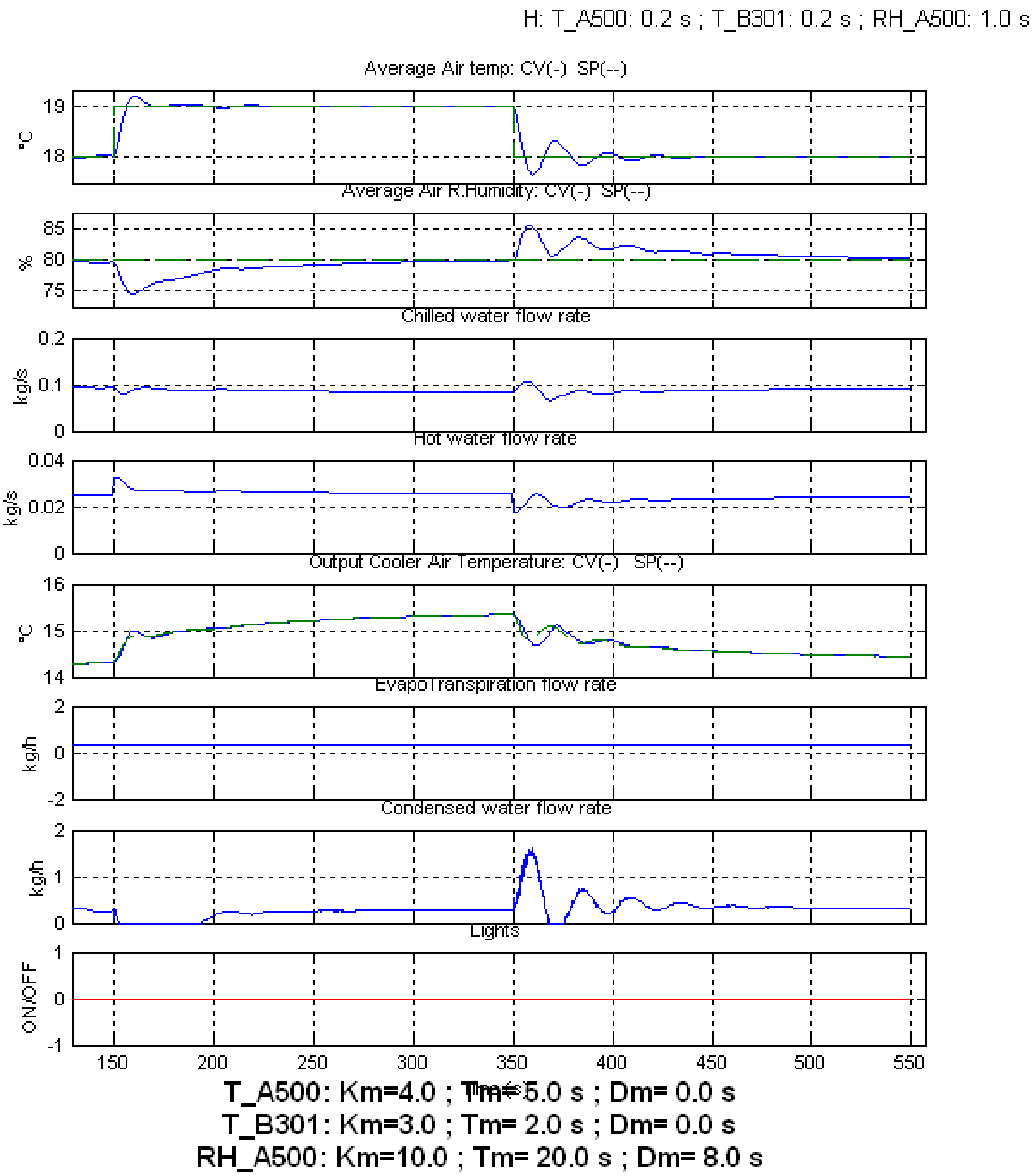


Figure 5.18 : Temperature set point steps with constant RH setpoint

5.4.4. Control of RH with constant air temperature setpoint

The Figure 5.19 shows that the closed loop response time of RH is about 200 s for negative step and 150 s for positive one. The specified one is 70 s. The resulting one is longer because of the high value of the gain Km = 10 %/°C chosen to increase robustness. The oscillations of RH are due to the non minimal de-phasing and over-tensed behaviour of the transfer (see Figure 5.11). The RH oscillations induce the temperature oscillations during 50 s after each RH setpoint step.

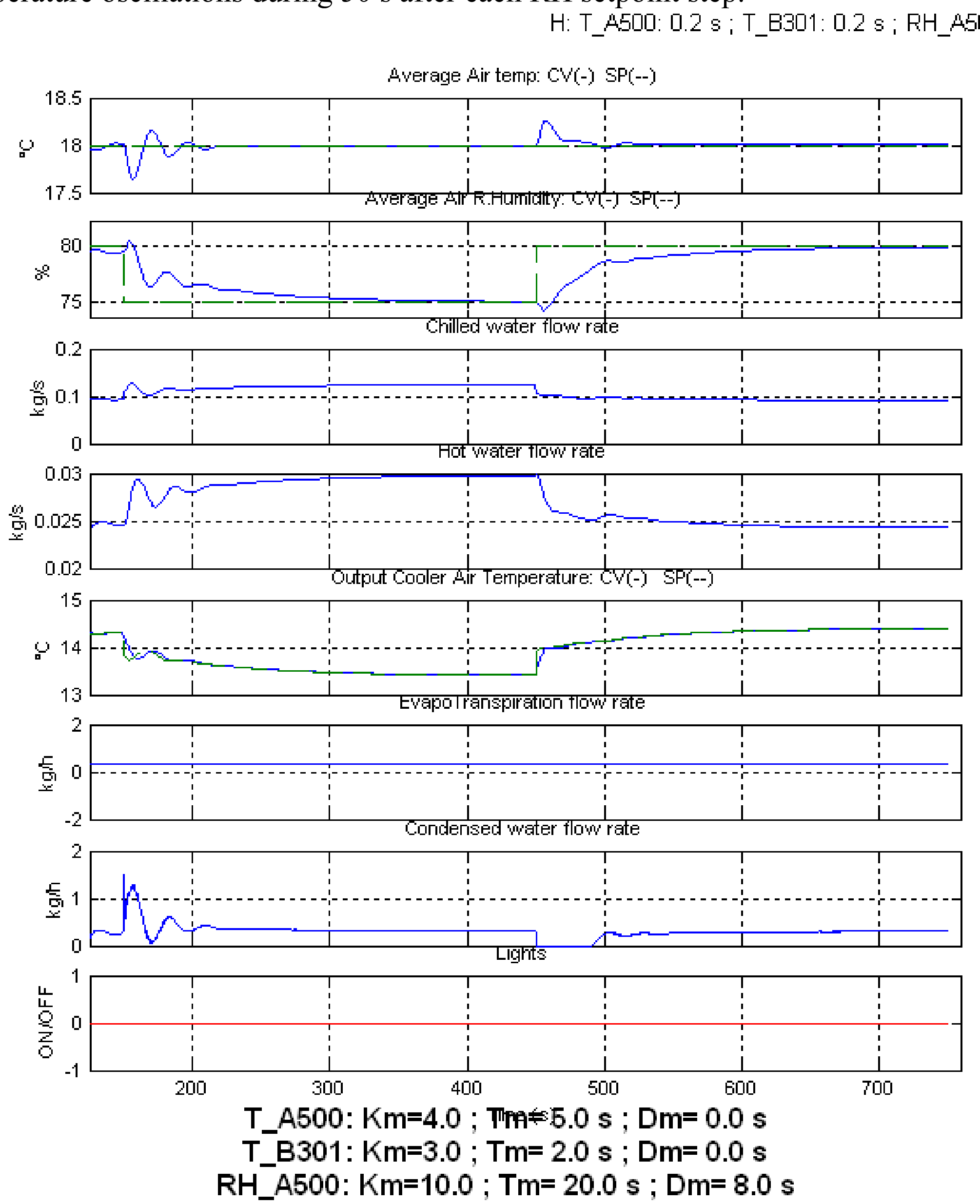


Figure 5.19 : Control of RH with constant air temperature setpoint

5.4.5. Simultaneous set points of temperature and RH

The set point steps are done at same time and in same direction (Figure 5.20**) :**
Both control of T & RH are oscillating (oscillations are due to RH control). The RH presents non minimal de-phasing behaviour. Simultaneous variations in opposite directions are easier to control (Figure 5.21).

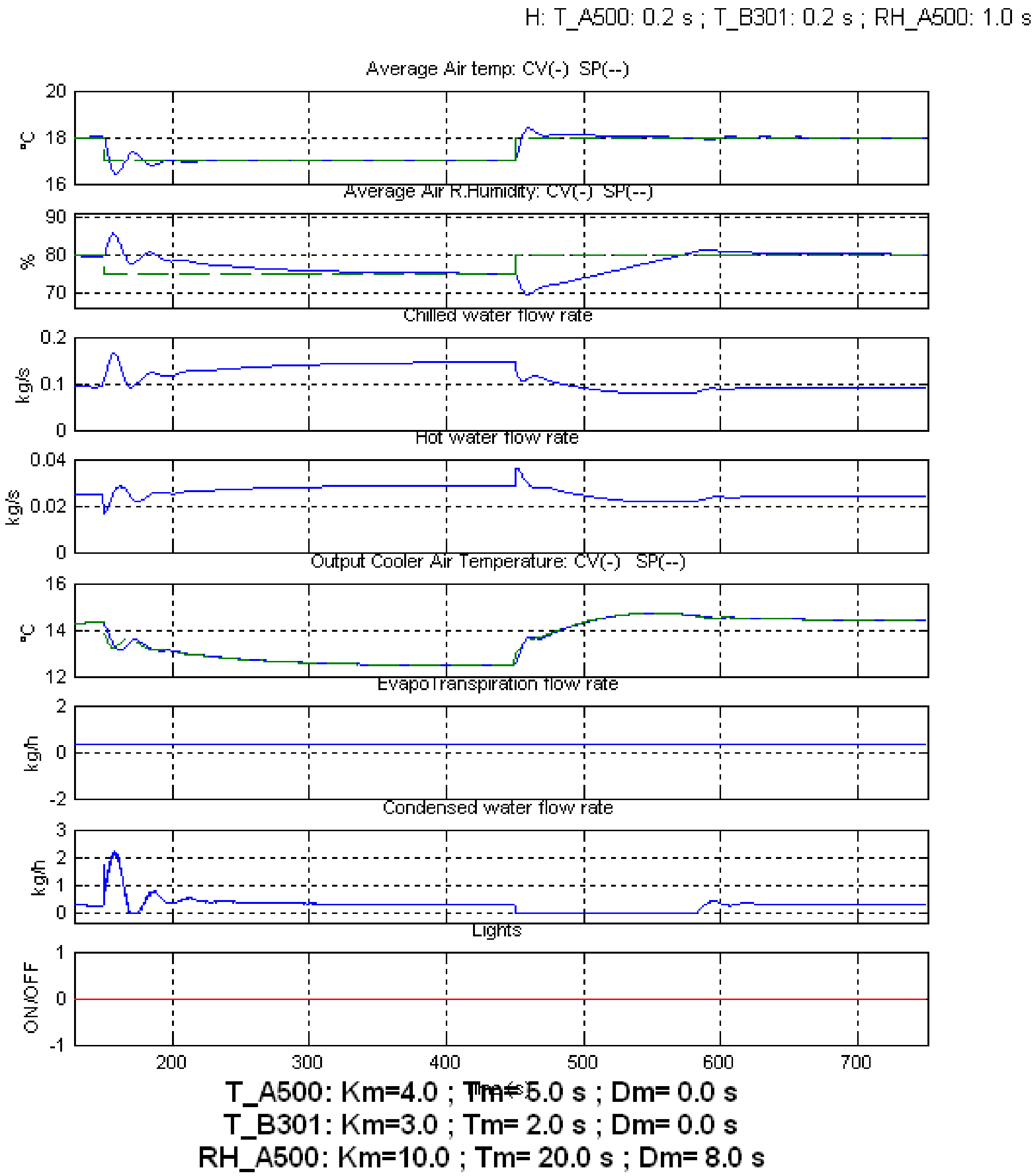


Figure 5.20 : Simultaneous set points of temperature and RH in same direction

The set point steps are done at same time and in opposite direction (Figure 5.21**) :** The control of temperature and RH is good. The non minimal de-phasing behaviour of RH is cancelled and replaced by an overshoot of 20 % of the set point step.

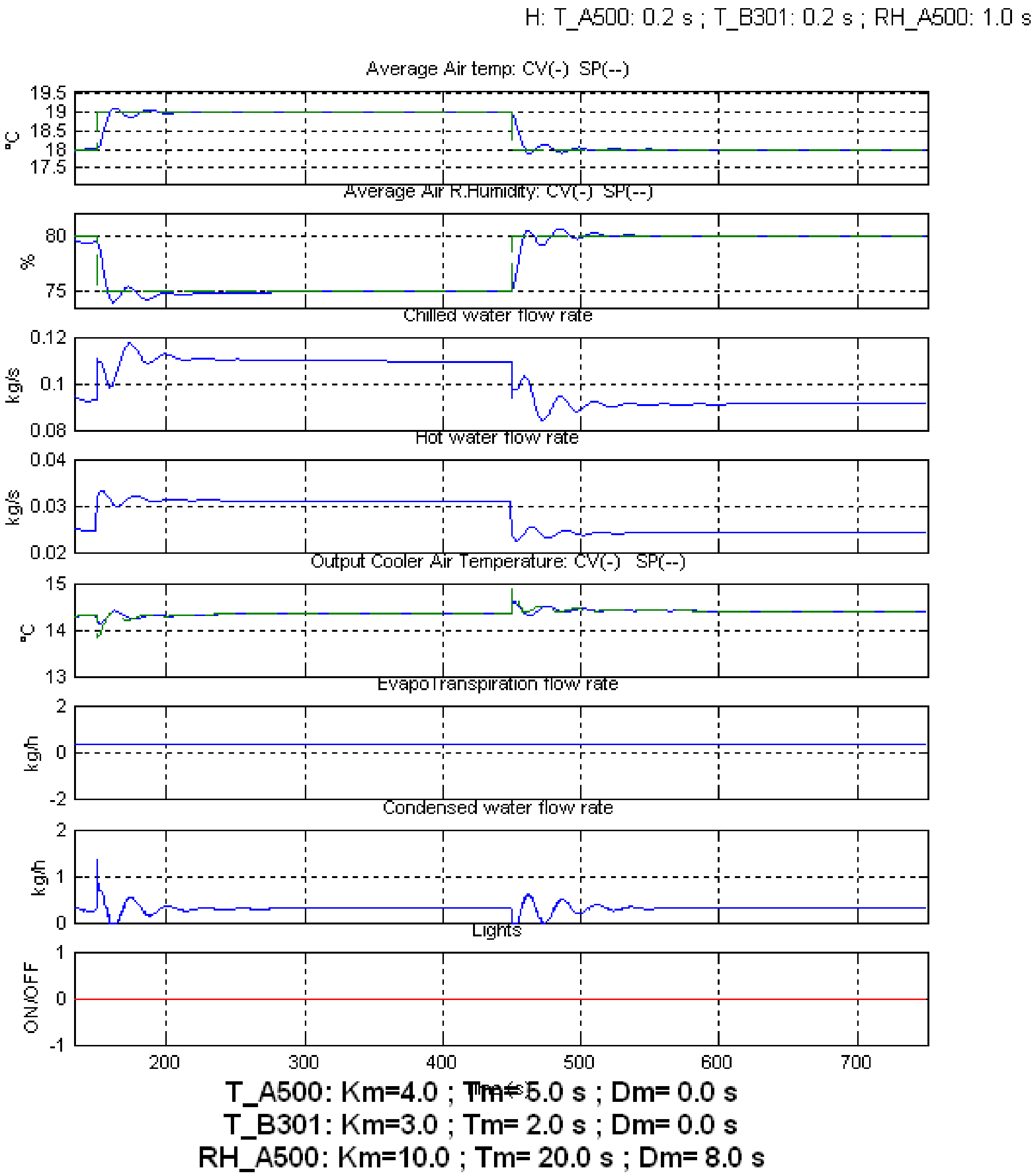


Figure 5.21 : Simultaneous set points of temperature and RH in opposite directions

5.4.6. Decreasing set point steps of RH from 80 to 50 % with constant air temperature setpoint

5.4.6.1. *Air temperature of A500 set to 18 °C*

For this simulation, the temperature & maximum flow rate of chilled water are set to 8.3 °C & 3 kg/s, respectively. Successive negative steps of 5 % of RH set point are applied.
Control is quite good. At 18 °C, the RH cannot go below 57 % (the setpoint of 50 % cannot be reached) because of technological limitation : the chilled water temperature is not low enough. When RH is below 70 %, its control is no more oscillating (see zoom on next Figure 5.23).

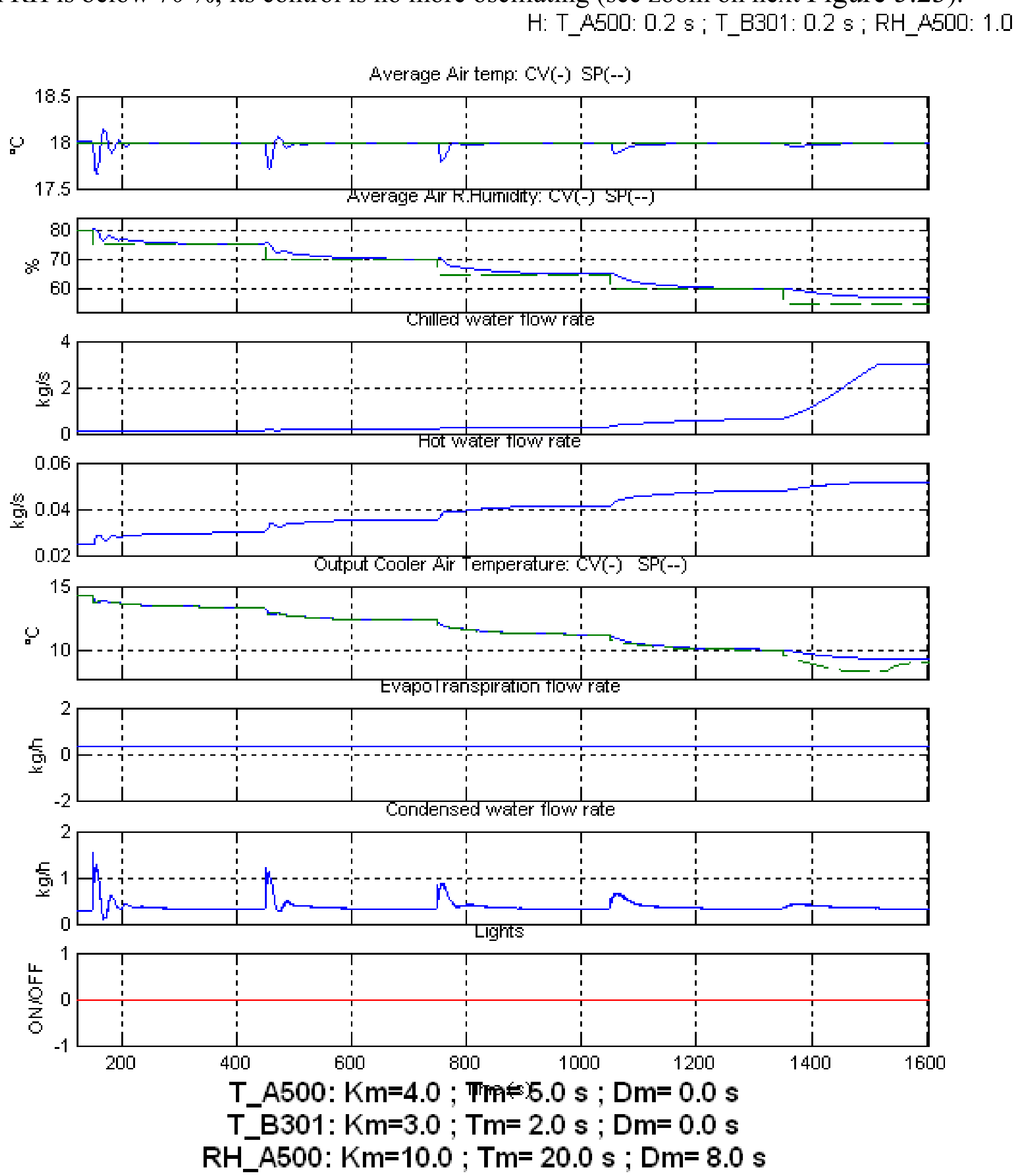


Figure 5.22 : Decreasing set point steps of RH (temperature of air set to 18 °C)

Zoom of previous simulation for RH below 70 %.

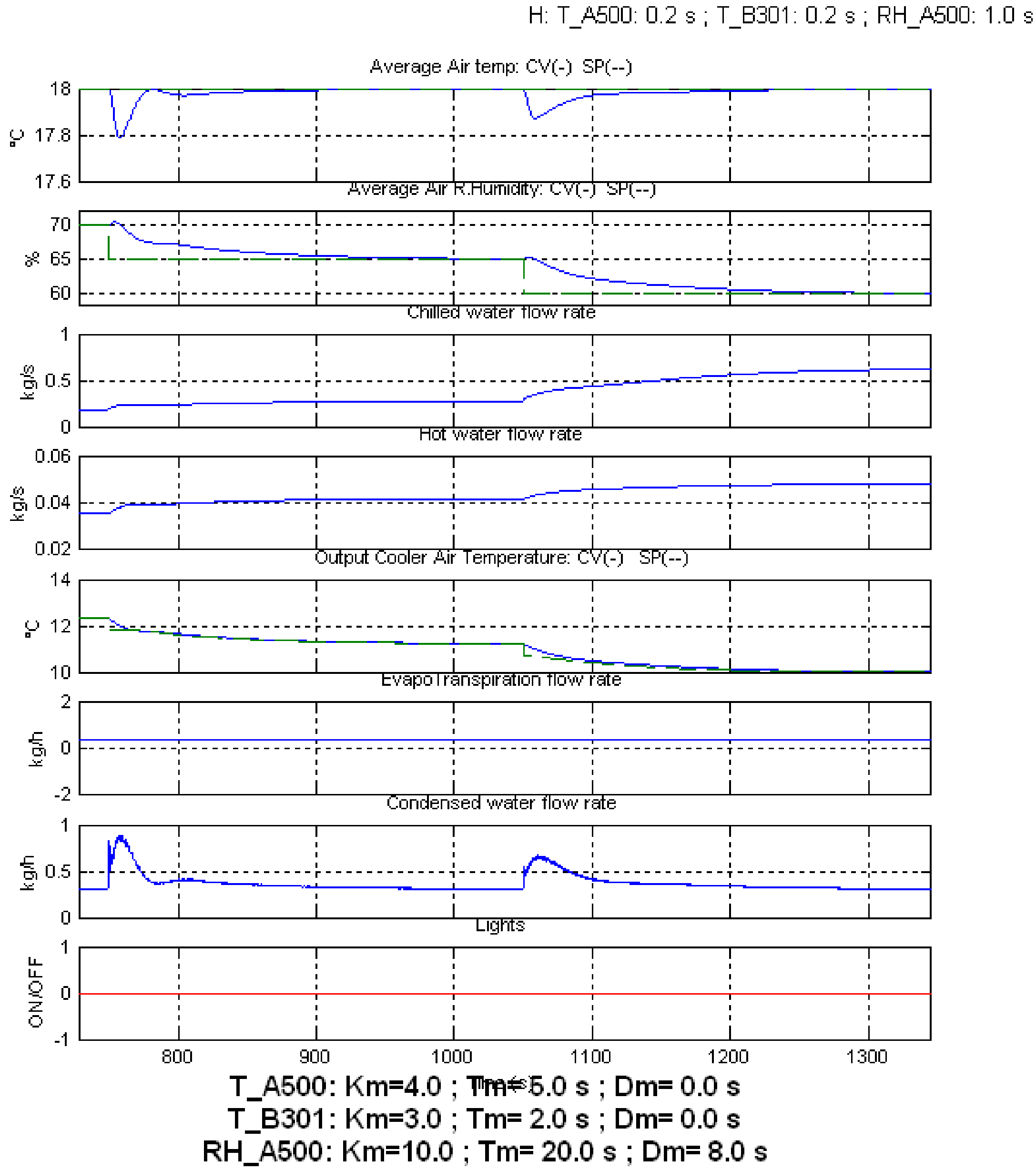


Figure 5.23 : Decreasing set point steps of RH (temperature of air set to 18 °C) (Zoom of previous figure).

5.4.6.2. *Air temperature of A500 set to 22 °C*

For this simulation, the temperature & maximum flow rate of chilled water are set to 8.3 °C & 3 kg/s, respectively. Successive negative steps of 5 % of RH set point are applied. Control is quite good. At 22 °C, the RH can reach 55 % easily.

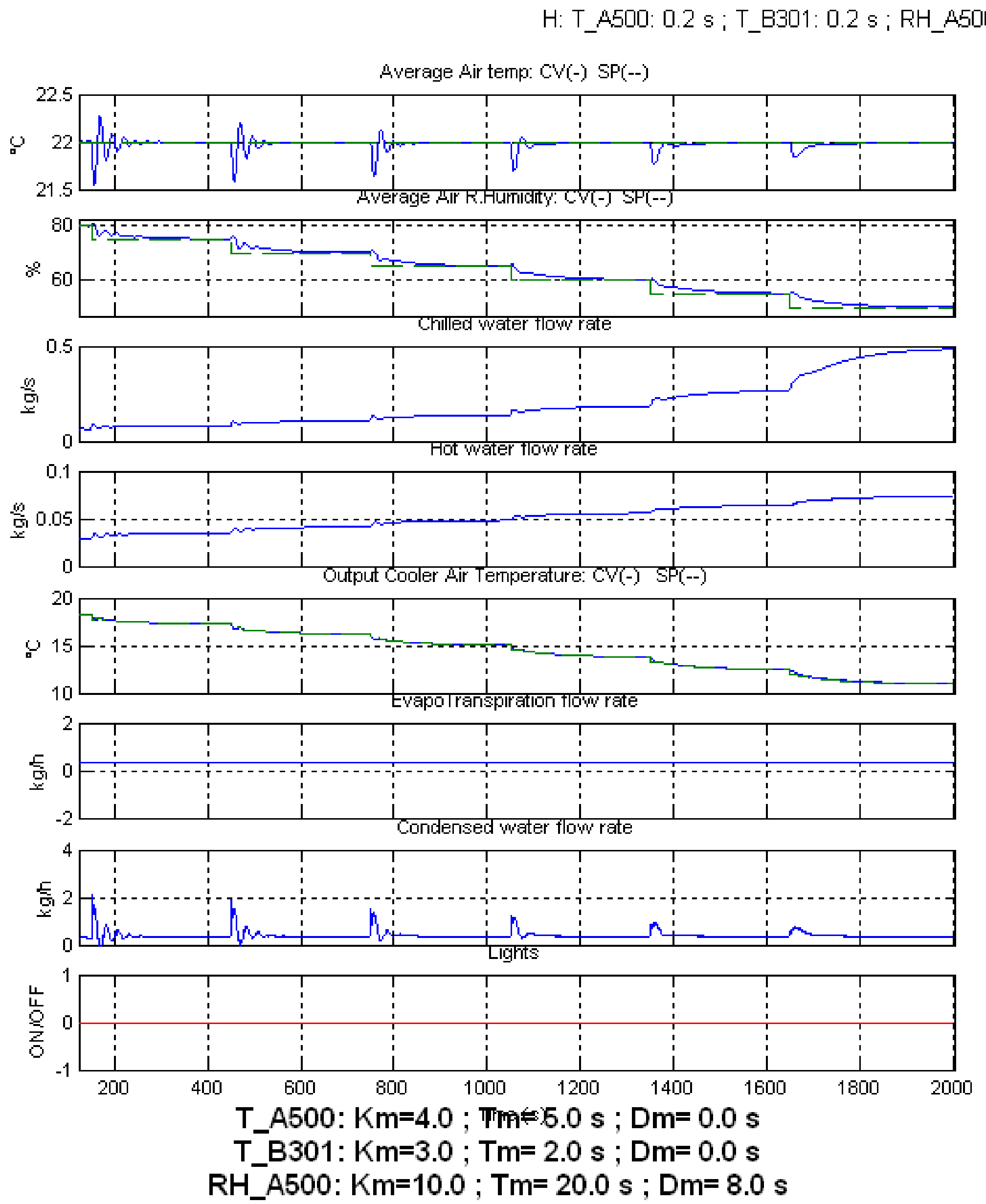


Figure 5.24 : Decreasing set point steps of RH (temperature of air set to 22 °C)

5.4.7. Time variable disturbance : random evapo-transpiration

The following simulation is done with constant temperature & RH set points. Exceptionally temperature of chilled water is set to 4 °C instead of 8.3 °C. Random evapo-transpiration flow rate is applied.

Control is quite good : the air temperature remains in a channel of 0.1 °C maximum amplitude and the RH in a channel of 1 % maximum amplitude.

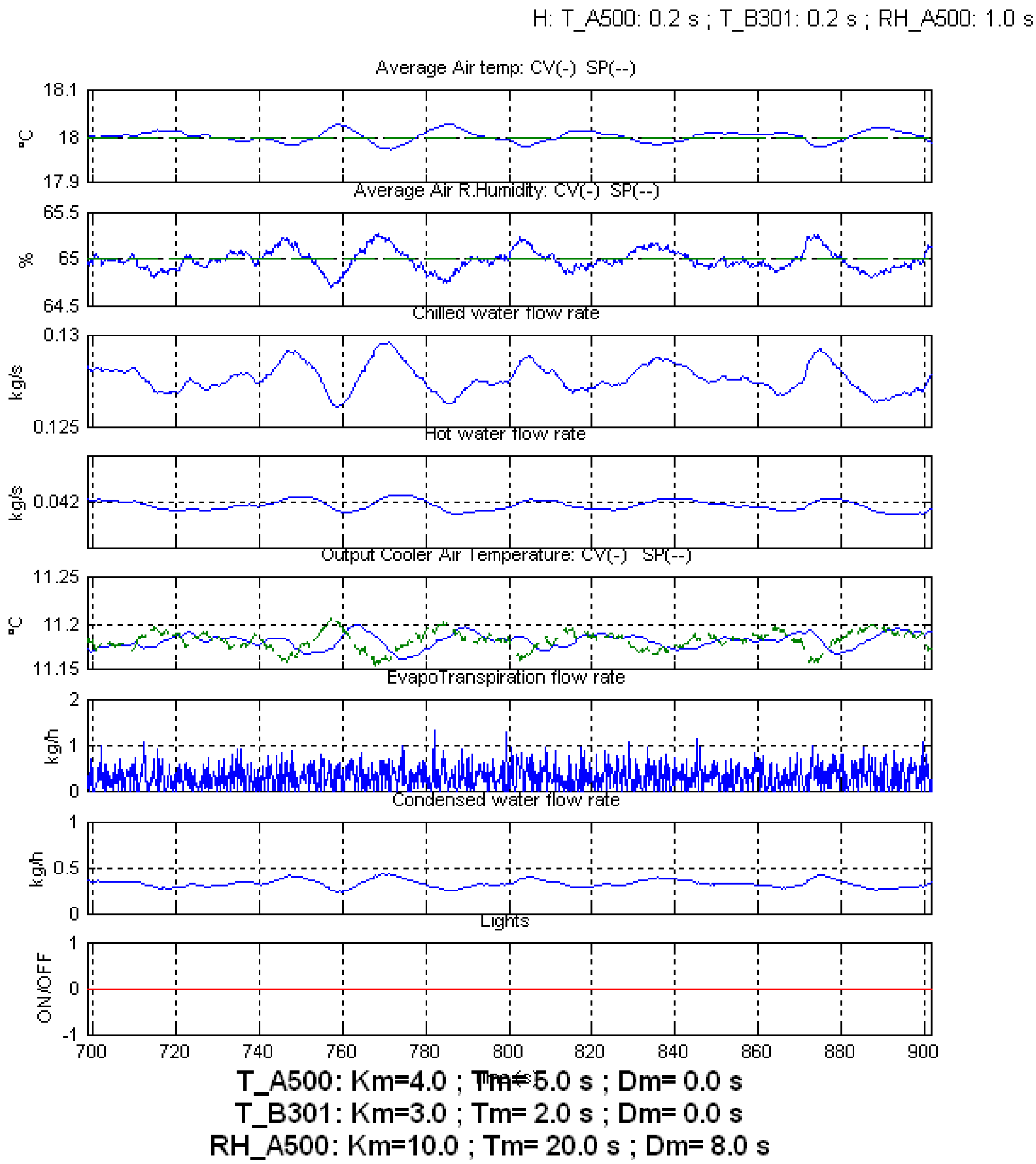


Figure 5.25 : Time variable disturbance : random evapo-transpiration

5.4.8. Time variable disturbance : steps of evapo-transpiration

The following simulation is done with constant temperature & RH set points. Exceptionally temperature of chilled water is set to 4 °C instead of 8.3 °C. Steps of evapo-transpiration flow rate are applied from 0 to double the mean flow rate value.

Control is quite good : the air temperature remains in a channel of 0.2 °C maximum amplitude and the RH in a channel of 2 % maximum amplitude.

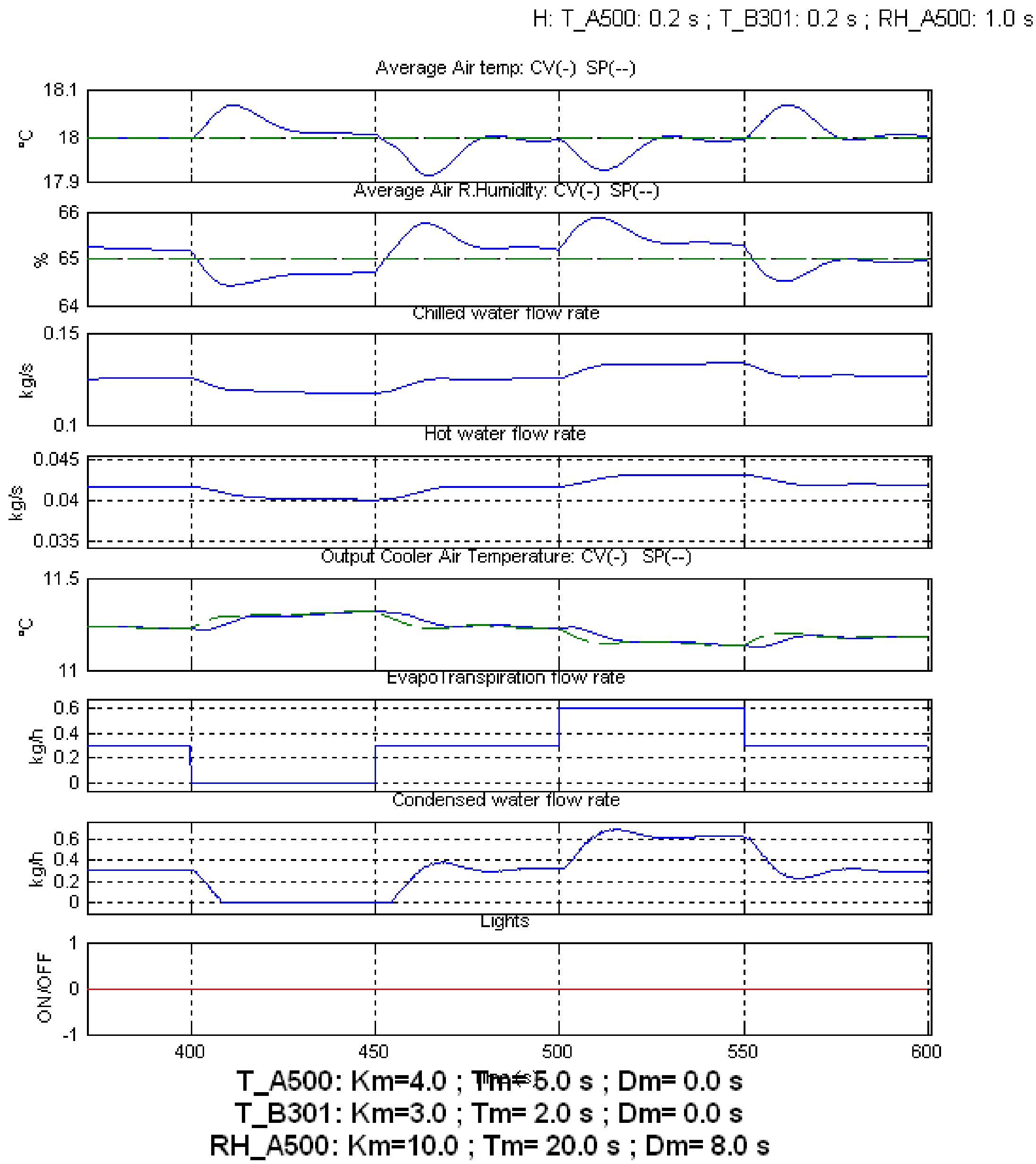


Figure 5.26 : Time variable disturbance : steps of evapo-transpiration

5.4.9. Time variable disturbance : steps of light flux

The following simulation is done with constant temperature & RH set points. Exceptionally temperature of chilled water is set to 4 °C instead of 8.3 °C. Steps of light flux are applied.

Despite the high value of the light flux steps, the control is quite good : the air temperature remains in a channel of 2 °C maximum amplitude and the RH in a channel of 4 % maximum amplitude.

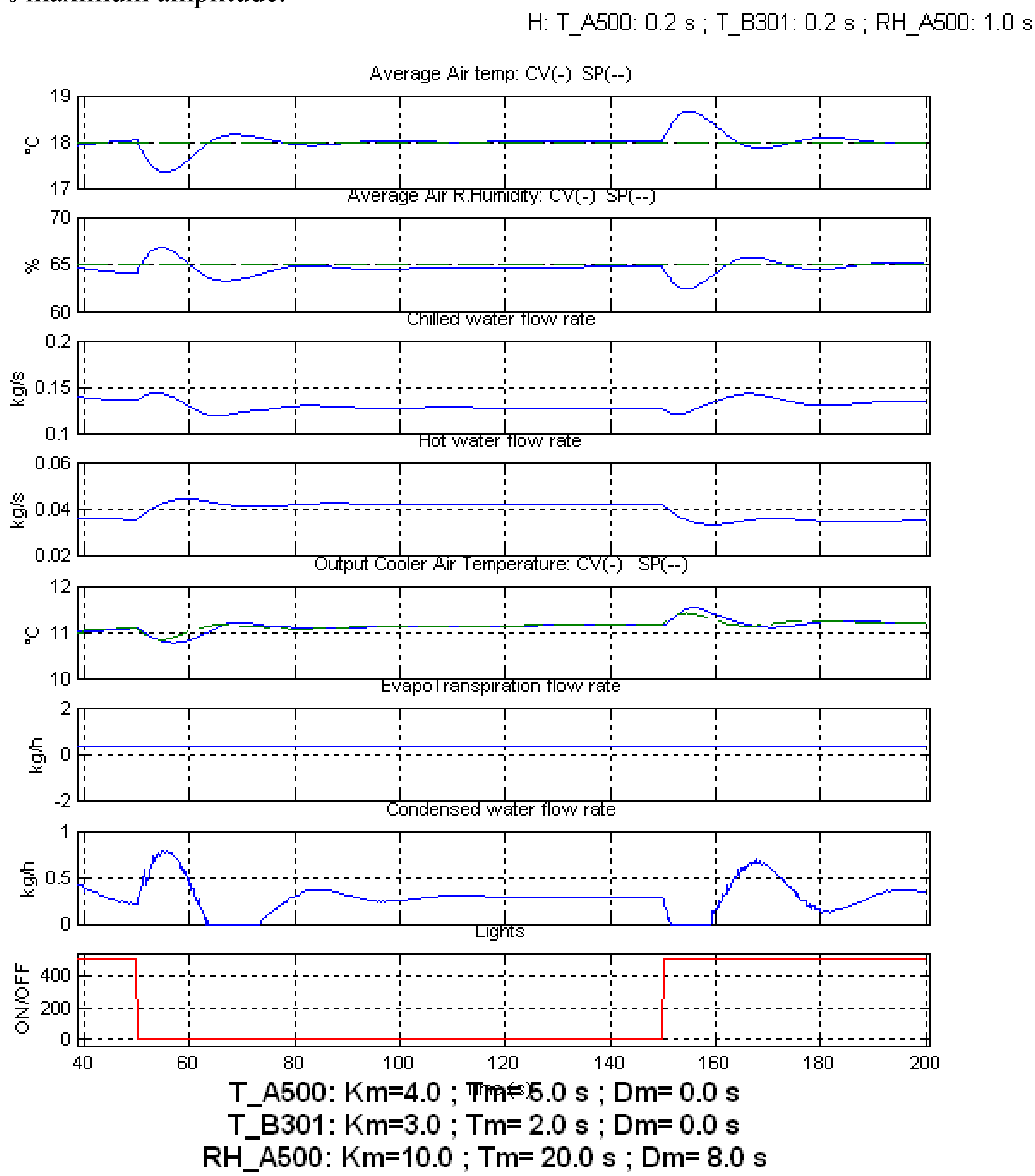


Figure 5.27 : Time variable disturbance : steps of light flux

5.4.10. Time variable disturbances : steps of evapo-transpiration & of light

The following simulation is done with constant temperature & RH set points. Exceptionally temperature of chilled water is set to 4 °C instead of 8.3 °C. Steps of light flux & evapo-transpiration flow rate are applied.

Control is quite good. When the evapo-transpiration is null (between t = 50 & t = 150 s), the RH setpoint cannot be reached : RH remains at 63 % when its setpoint is at 65 %.

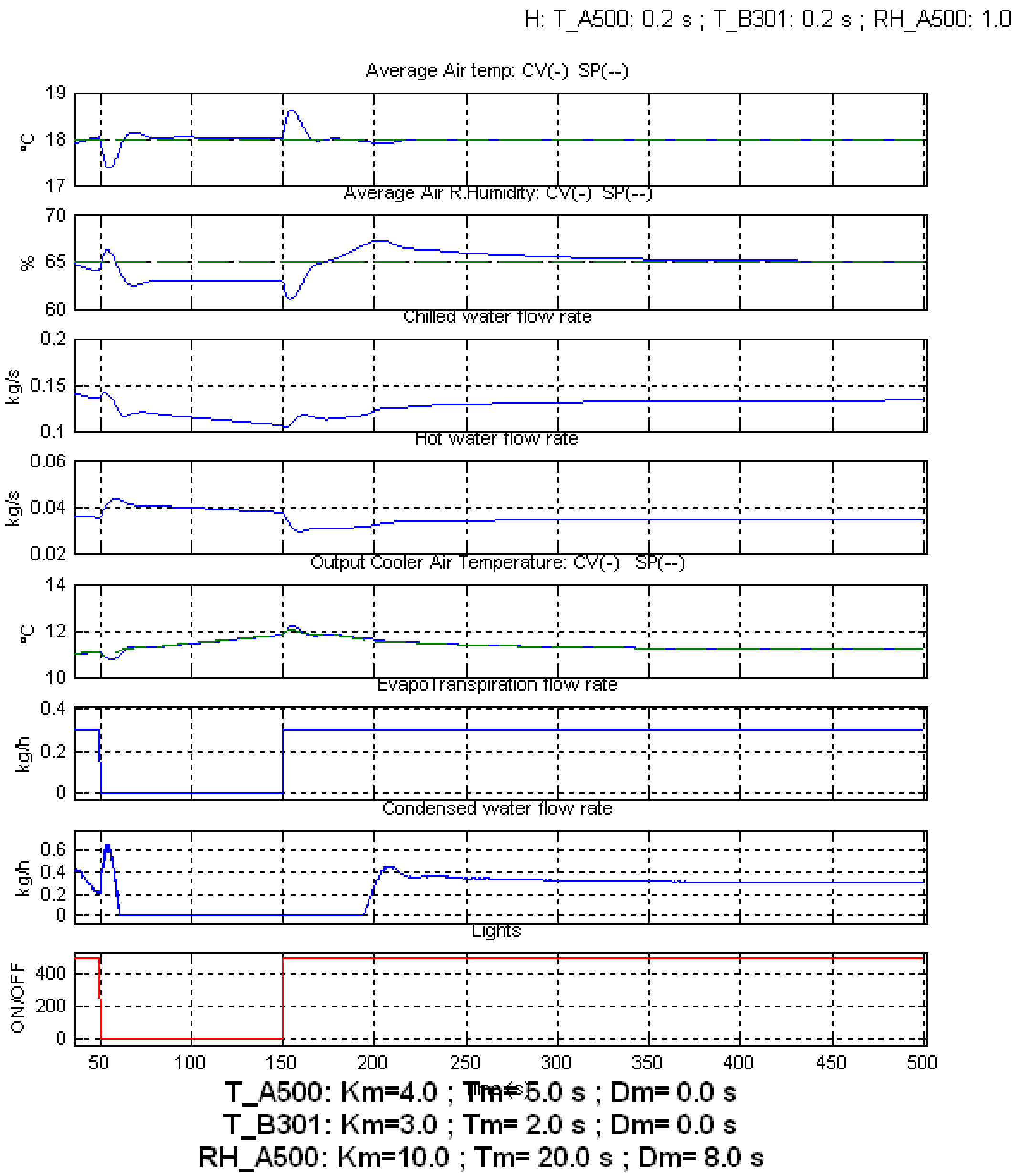


Figure 5.28 : Time variable disturbances : steps of evapo-transpiration & of light

5.4.11. Test of constraints transferring of the RH cascade

For these simulations the temperature and the maximum flow rate of chilled water are set to 4 °C and 0.25 kg/s, respectively so that the min & max constraints of chilled water flow rate can be reached. The test consists in big RH setpoint squares of 200 s length (done at t = 50 & t = 600 s) to put the chilled water flow rate on its constraints : the first square checks the technique on the min constraint and the second square the maximum one.

No constraints transferring (Figure 5.29)**:**
In Figure 5.29, the simulation is done without constraints transferring in order to be used as reference and to show the benefit of this technique.
Minimum constraint:
On graph 5, the setpoint (doted green curve) of Output Cooler Air Temperature setpoint drifts up to 25 °C without taking into account that the CV cannot go above 19 °C. At the end of the setpoint square (at t = 250 s), the MV of the master controller starts from 25 °C (and not from 19 °C). That implies the RH setpoint to be reached at t = 580 s.
Maximum constraint:
When the chilled water flow rate reaches its maximum (0.25 kg/s) just after the step at t = 600 s, the setpoint of Output Cooler Air Temperature drifts down to 4 °C (temperature of chilled water) without taking into account that the CV cannot go below 9 °C. At the end of the setpoint square (at t = 800 s), the MV of the master controller starts from 4 °C (and not the 9 °C). That implies the RH setpoint to be reached at t = 1050 s.

Constraints transferring (Figure 5.30)**:**
Minimum constraint:
With the constraints transferring technique, the Output Cooler Air Temperature setpoint (graph 5, doted green curve) does not drift and stays near the maximum value reached by the Controlled Variable (19 °C). At the end of the setpoint square (at t = 250 s), the MV of the master controller starts from 19 °C. That implies the RH setpoint to be reached at t = 480 s, 100 s earlier than without constraints transferring.
Maximum constraint:
In the same way, when the chilled water flow rate reaches its maximum (0.25 kg/s) just after the step at t = 600 s, the setpoint of Output Cooler Air Temperature does not drift and stays near the minimum value reached by the Controlled Variable (9 °C). At the end of the setpoint square (at t = 800 s), the MV of the master controller starts from 9 °C. That implies the RH setpoint to be reached at t = 900 s, 150 s earlier than without constraints transferring.

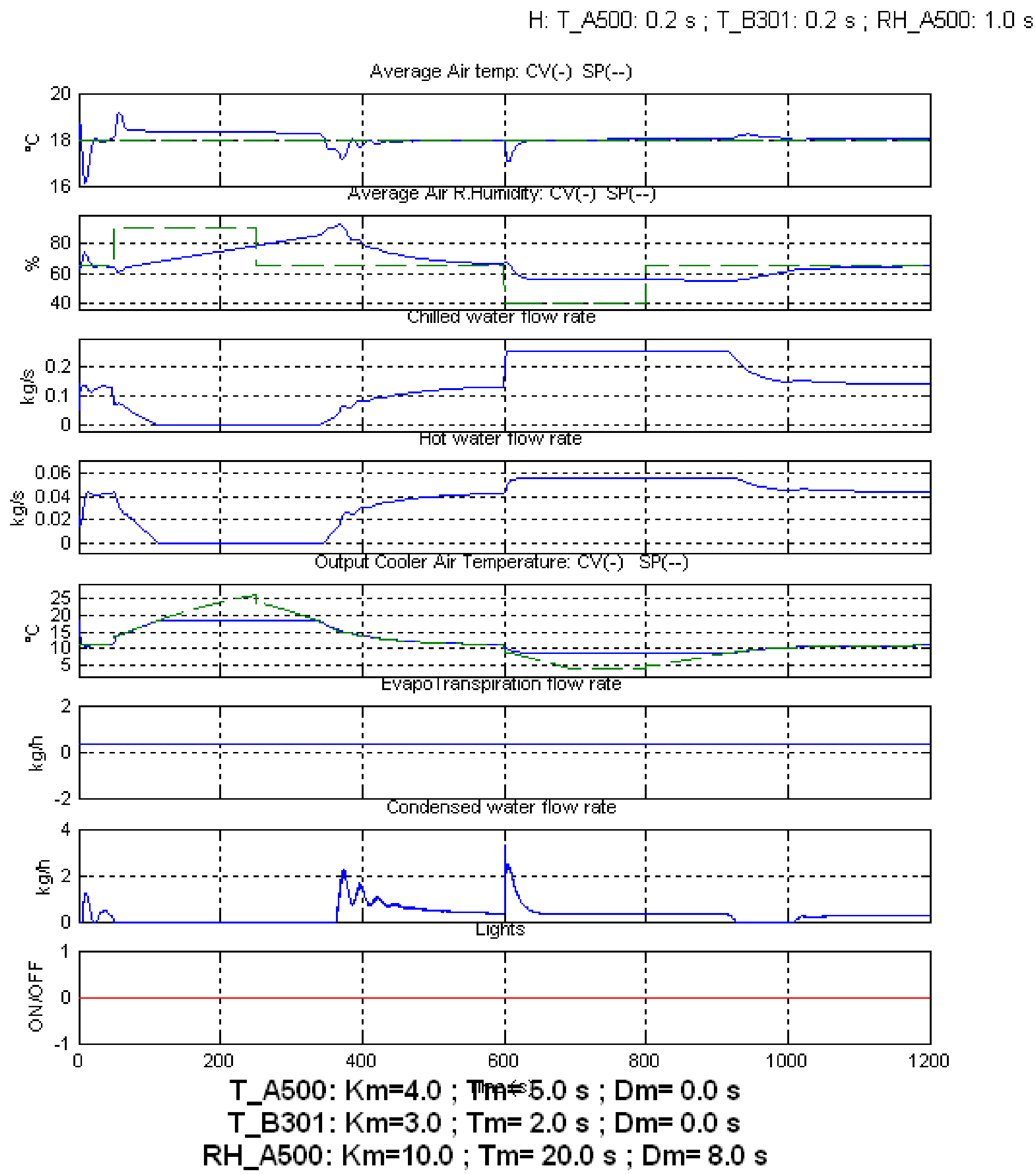


Figure 5.29 : Simulation without constraints transferring

(from slave to master controller of the RH cascade)

The following simulation is done with constraints transferring in the RH cascade control.

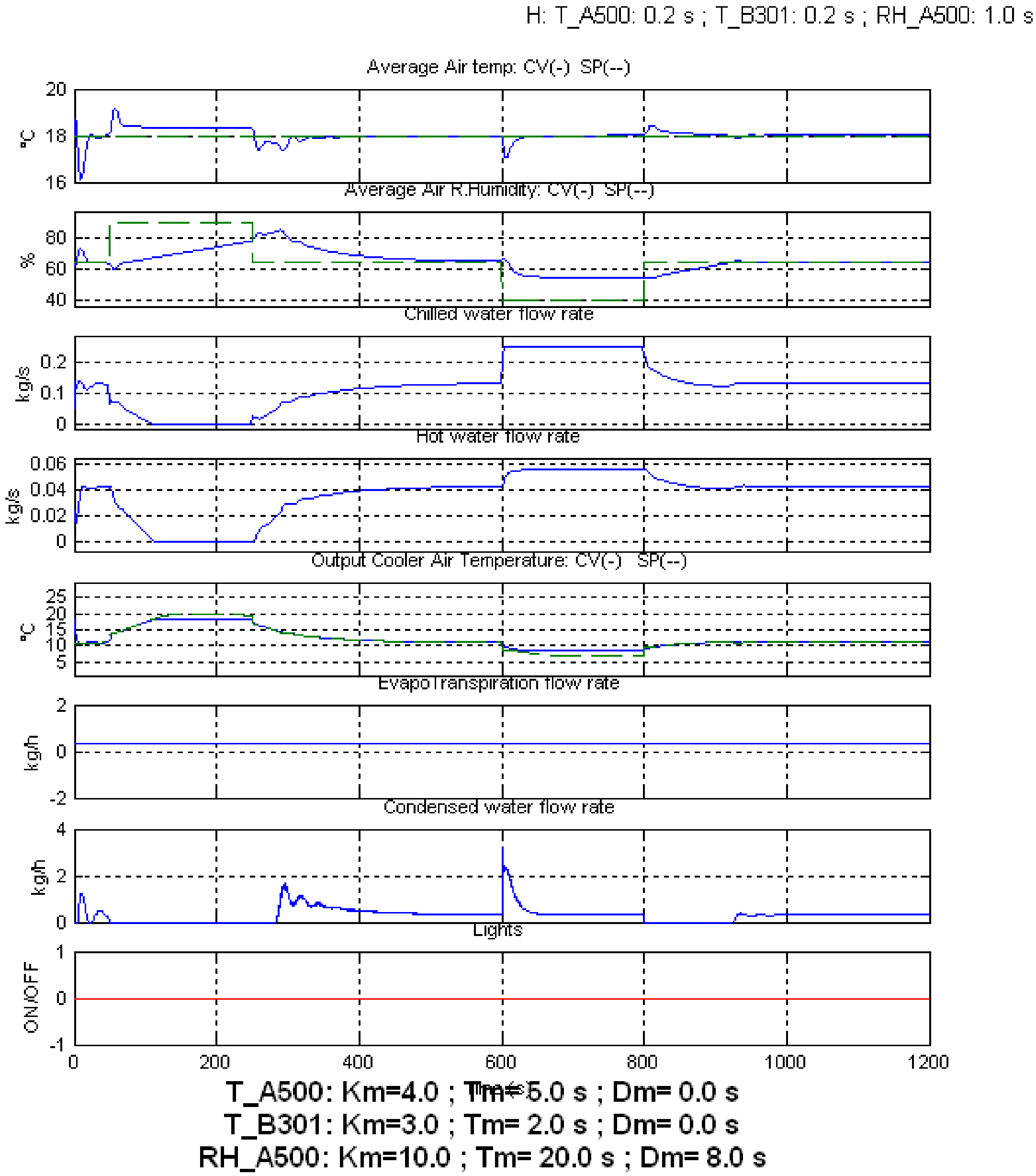


Figure 5.30 : Simulation with constraints transferring

(from slave to master controller of RH cascade)